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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This optoelectronic workshop represents the first of a series of intensive academic/government interactions in the field of advanced electro-optics as part of the Army sponsored University Research Initiative. The workshops are a collaboration between the Center for Opto-Electronic Systems Research at the University of Rochster, Rochester, New York and the U.S. Army Center for Night Vision and Electro-Optics, Ft. Belvoir, Virginia. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC.

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The Center for Night Vision and Electro-Optics

OPTOELECTRONIC WORKSHOPS

I

PHASE CONJUGATION/STRONGLY DRIVEN ATOMIC SYSTEMS

March 22, 1988

sponsored jointly by

ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester

OPTOELECTRONIC WORKSHOP

ON

PHASE CONJUGATION/STRONGLY DRIVEN ATOMIC SYSTEMS

Organizer: ARO-URI-University of Rochester
and Center for Night Vision and Electro-Optics

1. INTRODUCTION

This workshop represents the first of a series of intensive academic government interactions in the field of advanced electro optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO URI) and Dr. Rudy Buser, NVEOC.

2. SUMMARY AND FOLLOW-UP ACTIONS

Dr. Buser opened up the meeting with initial remarks on the true driving force of NVEOC tech base mission. It consists in introducing new technology in the military arena to address areas of deficiencies in Army programs. This introduction included the use of phase conjugation for solving problems in laser development for military application. Dr. Buser also stressed the point (has he did many times during the meeting) that the technology being developed must consider the requirements necessary for fieldable laser systems.

The first presentation was on the use of stimulated Brillouin scattering for solid state lasers presented by Richard Utano of NVEOC. It highlighted the past work done at Night Vision in this field, namely phase conjugation and its importance to solid state laser development; and some technical issues that still need to be resolved. Issues such as competing nonlinear processes and energy scaling were of utmost importance to the Army.

The next presenter was Dr. Ed Sharp and he described the effort NVEOC is planning in photorefractive materials. This work on characterizing materials and determination of necessary laser parameters for filters and other applications, generated much interest with the Rochester personnel, especially Dr. Sharp's work with the tungsten bronze crystals.

To complete discussion of NVEOC interest in phase conjugation, Dr. Lynn Garn presented phase conjugation potential for neural networks for automatic target recognition. Though the properties of optical phase conjugation are not exercised, there are similar techniques being employed for this optical computing process. This discussion was centered on NVEOC's view of the status of the technology, and its potential versus conventional electronic techniques.

Dr. Boyd then gave an overview of the Institute of Optics work in phase conjugation. He discussed work on single pass aberration correction, coherence issues of phase conjugated light, Brillouin enhanced four-wave-mixing and vector phase conjugation. The vector phase conjugation via stimulated Rayleigh wing scattering or other possible methods, generated interest by NVEOC personnel. Such a process could counter birefringence problems associated with high average power lasers.

Ken MacDonald, Post Doc, then presented work on laser beam combining in atomic vapors. Both probe beam amplification and beam combining experiments were discussed. To date, 25% energy transfer was obtained in Na vapor which is promising but the criteria for such effects are very frequency dependent.

These presentations were then followed by discussion on the many techniques each facility was experimenting on. Areas of overlap were discussed and ideas for potential collaboration were identified. The outcome implies that there are several areas where mutual interest exists: In the photorefractive field of phase conjugation, which is still undergoing vast amounts of basic research, the overlap and interest of the University is evident. In the field of stimulated scattering, the issues of concern are not necessarily fundamental, and overlap less directly with the University's goals.

On the basis of this workshop, the following ideas for continued interaction have been developed:

a. Photorefractive Nonlinear Optics

It would be interesting to perform additional measurements to establish that self-pumped phase conjugation in the tungsten bronzes is inherently more stable than in barium titanate, with roughly equivalent optical properties leading to PCM's with very different stability characteristics.

Also, it would be important to perform measurements to establish to what extent incoherent light (spatially and/or temporarily) can be used to excite nonlinear optical processes in these materials.

NVEOC could help to get started in these areas by helping to obtain photorefractive tungsten bronze crystals.

b. Laser Beam Combining

The University will try to establish the appropriate scaling laws for laser beam combining in atomic vapors, and from these scaling laws attempt to establish (through discussion with NVEOC personnel) applications in the field of laser development.

c. Vector Phase Conjugation

Vector phase conjugation appears to be a promising technique for removing the effects of thermally induced radial birefringence from laser rods Through discussions with NVEOC personnel and through laboratory measurements, the University will determine whether vector phase conjugation has implications to the NVEOC laser program.

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

RECENT RESULTS IN PHASE CONJUGATION

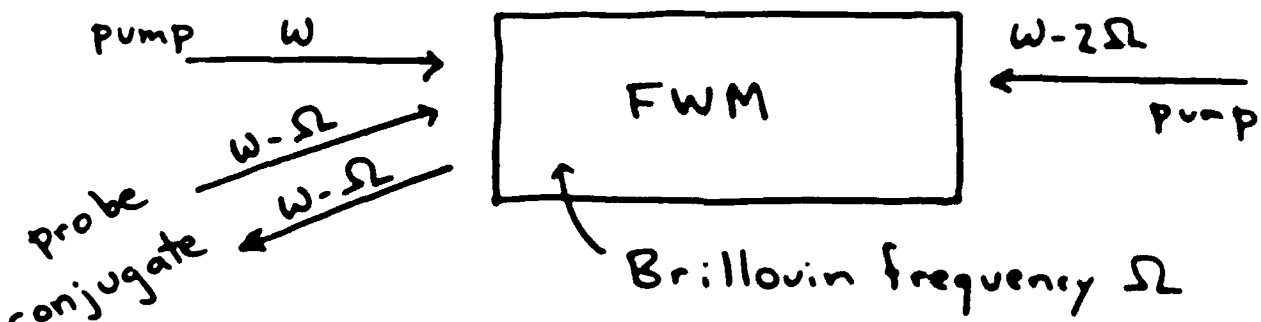
Research in Nonlinear Optics

Professor	
Robert W. Boyd	B.S., Massachusetts Institute of Technology Ph.D., University of California at Berkeley
Post Docs	
Michelle S. Malcuit	B.A., New York State University Ph.D., University of Rochester
Kenneth R. MacDonald	B.S., Worcester Polytechnic Institute M.A., Johns Hopkins University Ph.D., University of Southern California
Graduate Students	
Alexander L. Gaeta	B.S., University of Rochester M.S., University of Rochester
Daniel J. Gauthier	B.S., University of Rochester M.S., University of Rochester
Mark L. Gruneisen	B.A., Sate University College at Potsdam M.S., University of Rochester
Martti Kauranen	M.S., Helsinki University of Technology
Jeffery J. Maki	B.S., Lewis and Clark College
Edward Miller	B.S., University of Rochester M.S., University of Rochester
Mark D. Skeldon	B.S., Old Dominion University M.S., Old Dominion University M.S., University of Rochester
Bryan Stone	B.S., University of Rochester
Wayne R. Tompkin	B.A., Kenyon College
Secretary	
Lynne V. McCoy	B.A., University of Rochester

BRILLOUIN ENHANCED FOUR-WAVE MIXING

Signal and pump waves differ in frequency by Brillouin frequency of medium.

Four-wave mixing process mediated by intense sound wave.



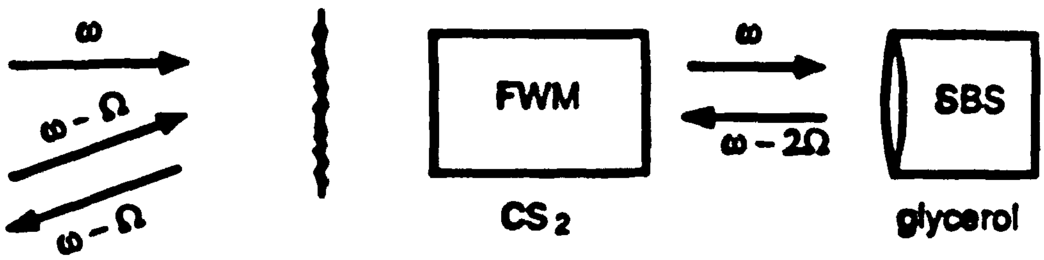
$$\Omega \equiv 2\omega \frac{v}{c/n}$$

Reflectivity can readily exceed 100%
No requirement on pump frequency
No frequency shift
Good energy transfer from pumps to conjugate

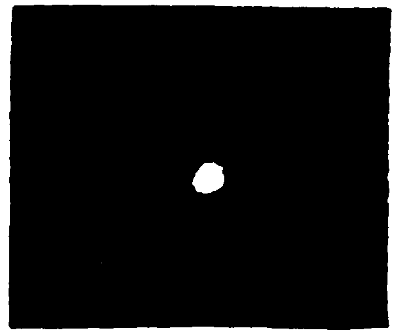
P. Narum and R W. Boyd, IEEE J. Quantum Electron (1987)

M. D. Skeldon, P. Narum, and R. W. Boyd, Opt. Lett. (1987)

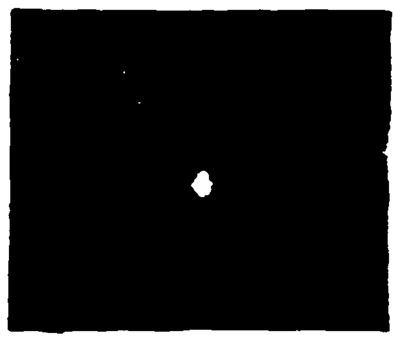
Phase Conjugation with Aberrated Pump Waves



PC signal
with no aberrator



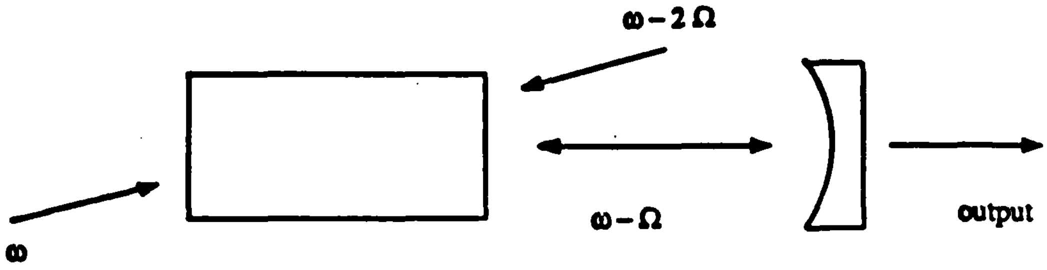
PC signal
with aberrated pump waves



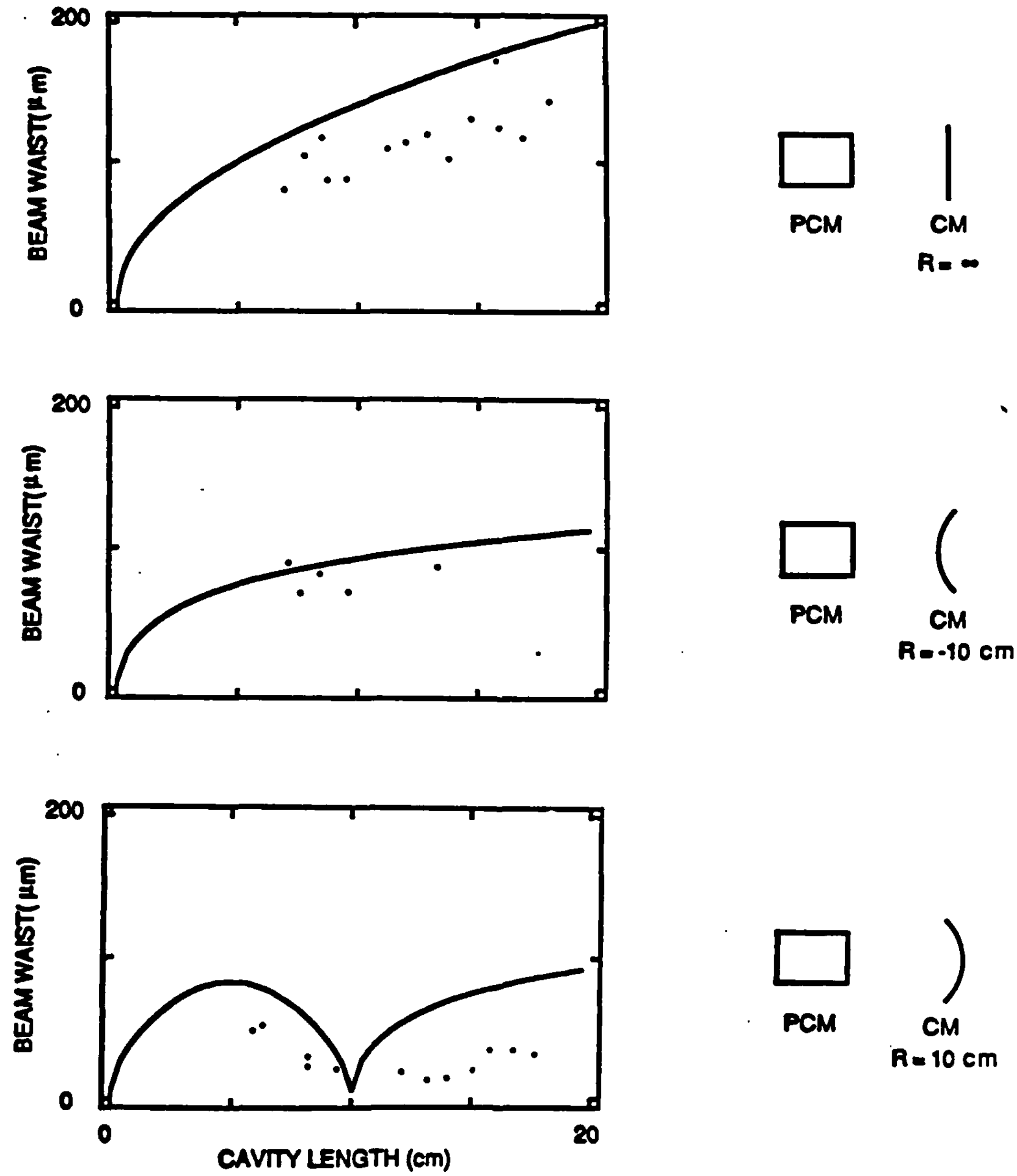
Degree of aberration
on the waves

Phase Conjugate Oscillator

Brillouin Enhanced Four Wave Mixing



Output beam characteristics

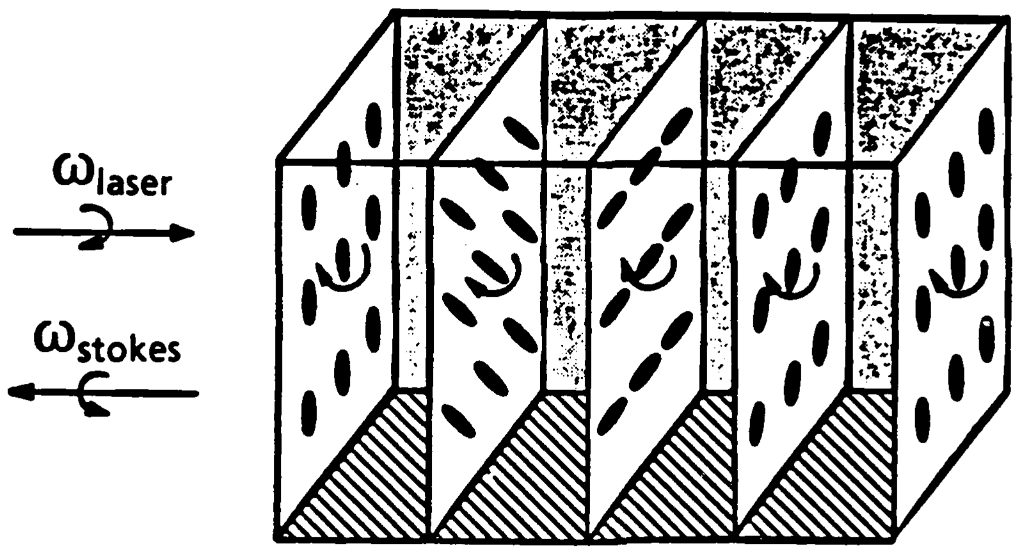


Phase Conjugation by Stimulated Rayleigh-Wing Scattering

- Provides complete vector phase conjugation
- Fast response time allows conjugation of picosecond pulses

Rayleigh-wing scattering:

Scattering from non-uniformly oriented anisotropic molecules.



Questions:

How does the SRWS treat circularly polarized light? Elliptically polarized light? Randomly depolarized light?

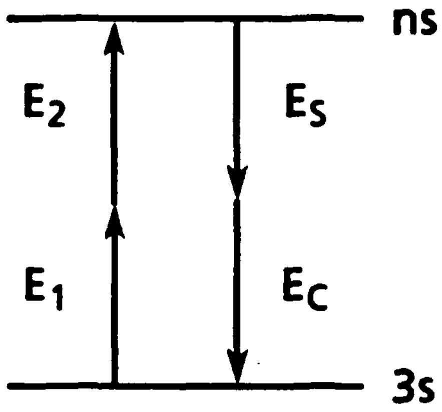
Competing effects: stimulated Brillouin scattering, stimulated Raman scattering, self focusing, self-phase modulation.

Vector Phase Conjugation by DFWM

$$\vec{E}_c = r\,\hat{\varepsilon}_s^* A_s^* e^{-ik_s z}$$

polarization conjugation   wavefront conjugation

Two-photon resonant enhancement:



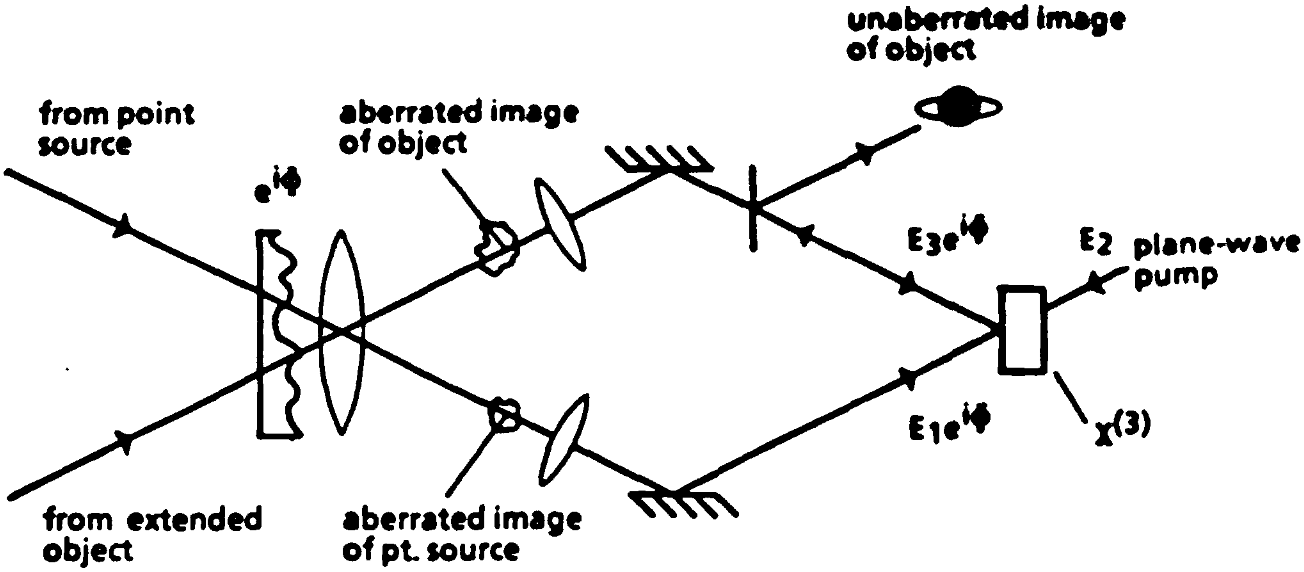
(Grynberg, 1984)

- Observed vector phase conjugation for <u>weak</u> pump intensities ($|r|^2 \sim 10^{-4}$)
- Observed degradation of the fidelity of phase conjugation for strong pump intensities ($|r|^2 \sim 10^{-2}$)

Next:

- Study effects of geometries
- Need to understand saturation effects in two-photon resonant systems

Single-pass Aberration Correction

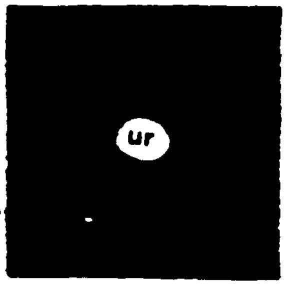


$$P_{NL} \sim (E_1 e^{i\Phi})E_2(E_3 e^{i\Phi})^* = E_1E_2E_3^*$$

Φ = phase distortion introduced by aberrator

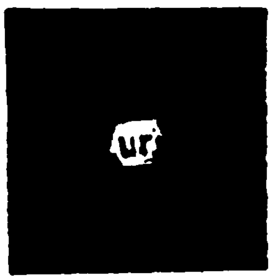
- Thin phase distorter
- Coherent imaging

(Goodman, 1966)



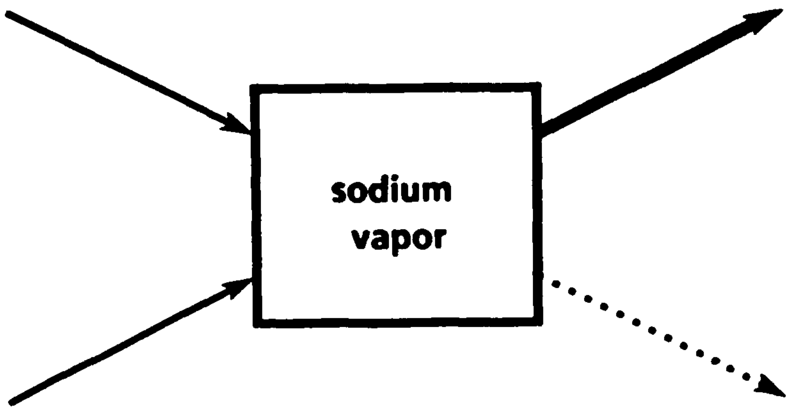
'ginal object

aberrated image
of object



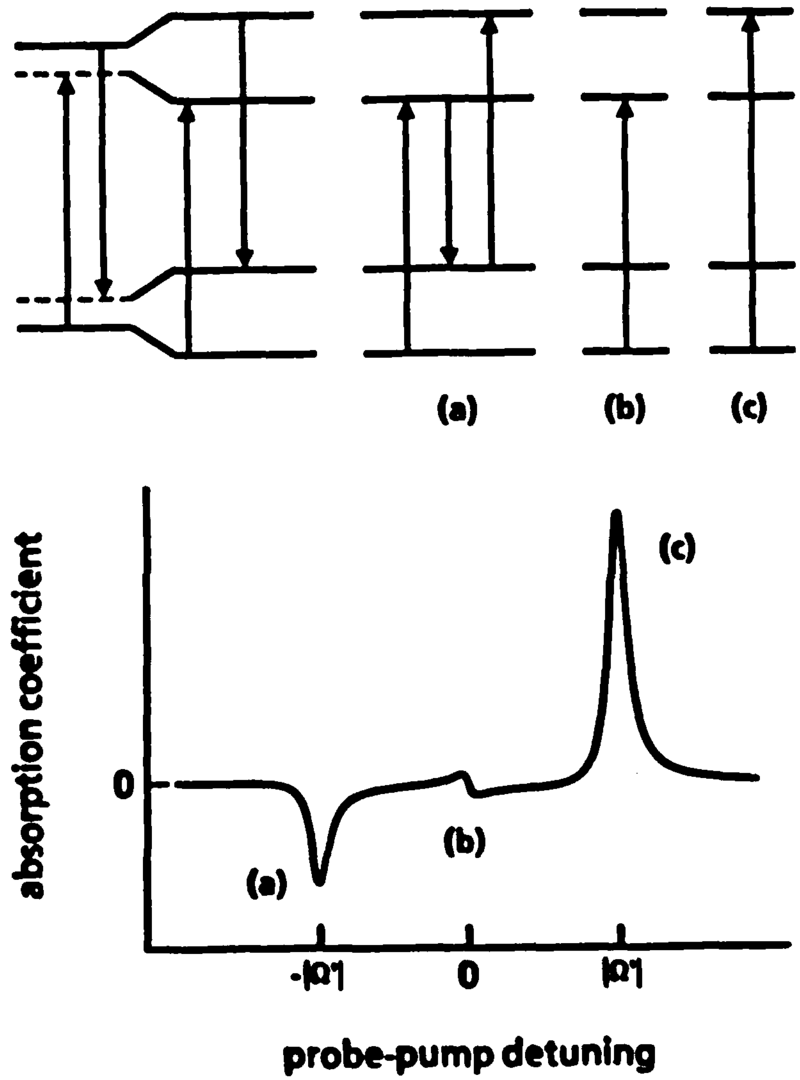
unaberrated image
recovered by
phase conjugation

LASER BEAM COMBINING IN SODIUM



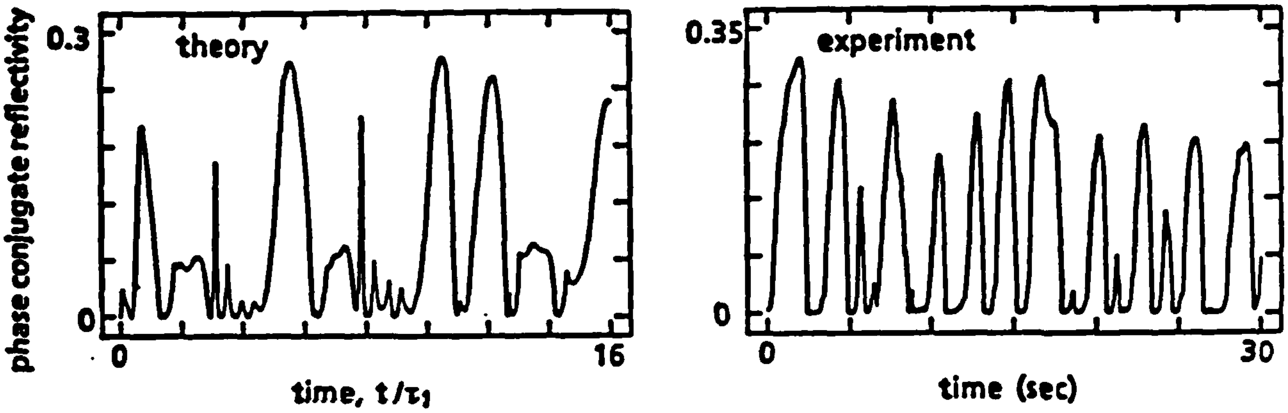
- 38-times increase in the intensity of a weak probe beam has been observed.
- Measurements of energy transfer for equal-intensity beams are now in progress.

DYNAMIC STARK EFFECT



Instabilities and Chaos in Phase Conjugation

Observed chaotic behavior in a
barium titanate,
internally self-pumped PCM.



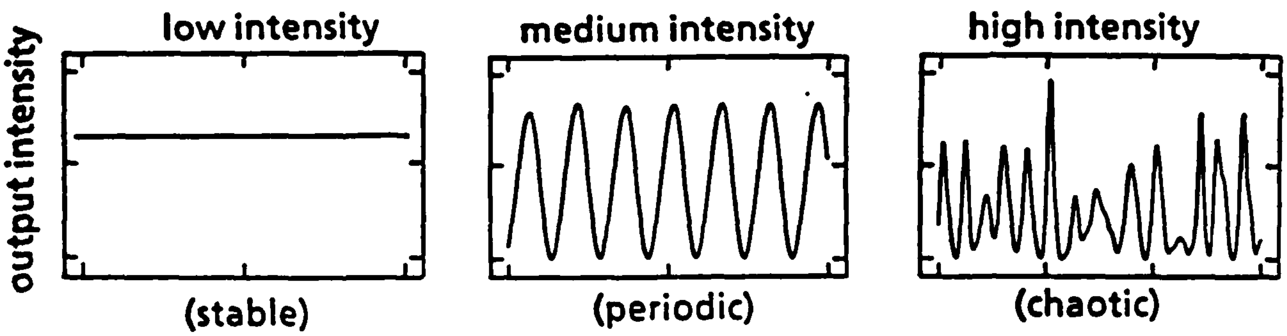
- Instability due to coupling between all four nonlinear refractive-index gratings.

- System evolves temporally on a strange attractor characterized by a
  correlation dimension $\nu = 1.3$
  and an
  order-2 Renyi entropy $K_2 = 7.2$ bits/sec.

Phys. Rev. Lett., 58, 1640 (1987)

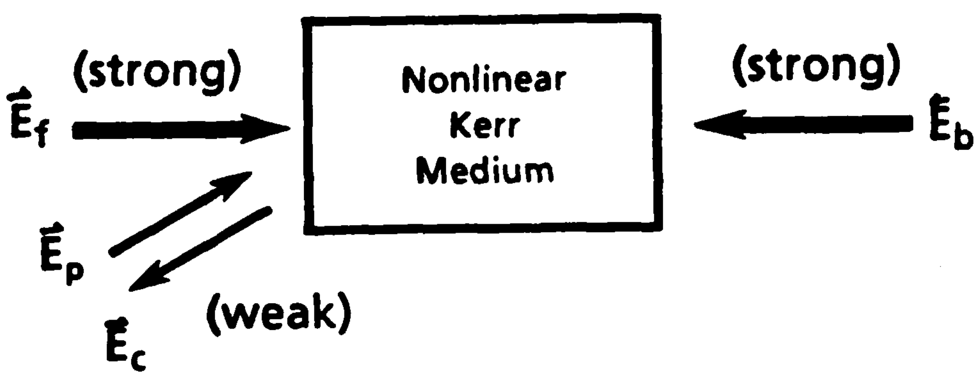
Temporal Instabilities of Counterpropagating Light Fields

- simple interaction can exhibit complex behavior
- output polarization and intensity can fluctuate periodically or chaotically in time



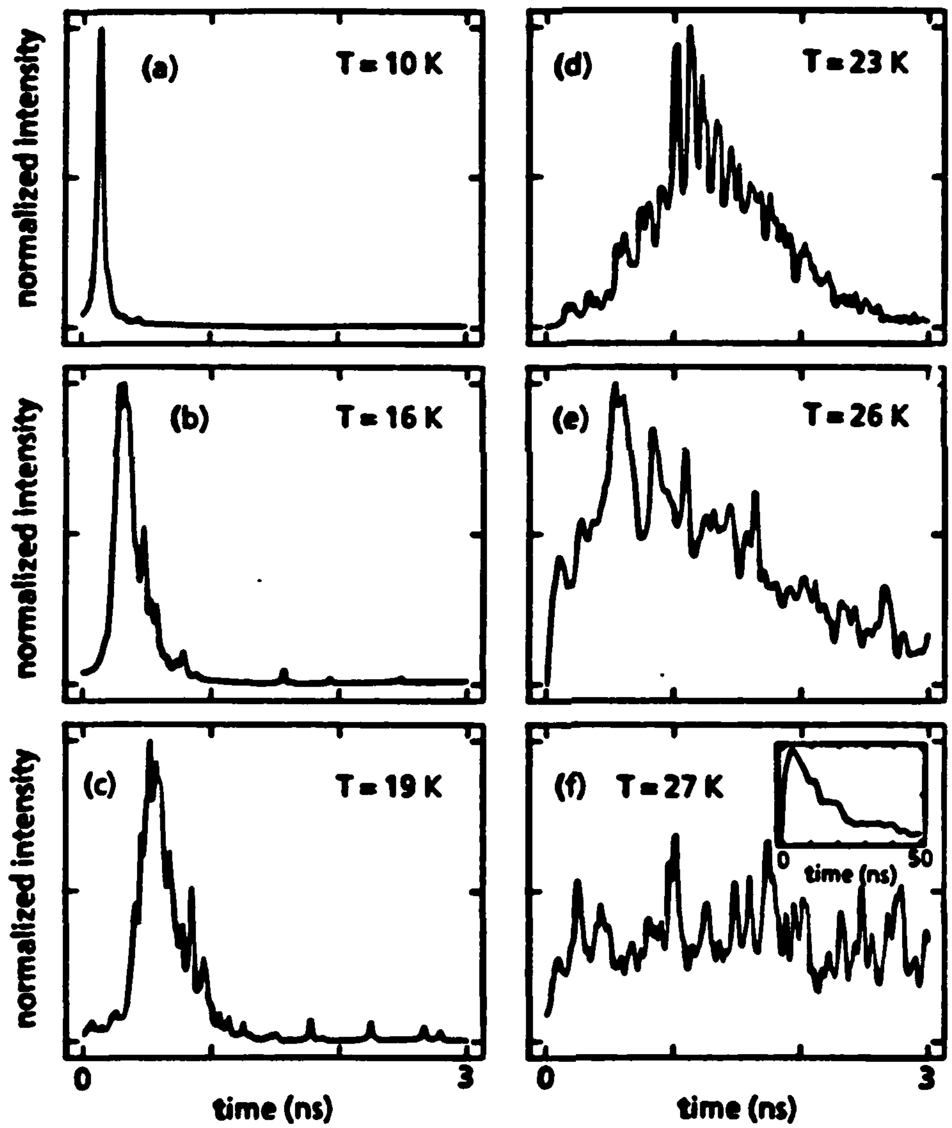
- instabiltity threshold is lower when tensor nature of the interaction is treated (Gaeta et al., Phys. Rev. Lett. (1987))

- limitation on performance of phase conjugation via FWM



What is the difference between superfluorescence and amplified spontaneous emission?

- Study the emission of $KCl:O_2$ as a function of temperature.

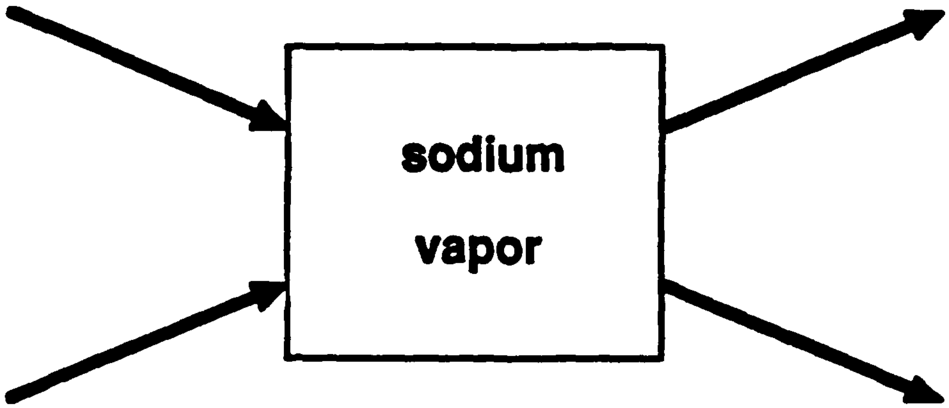


Malcuit, Maki, Simkin, and Boyd, Phys. Rev.Lett. (1987)

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

LASER BEAM COMBINING IN ATOMIC VAPORS

LASER BEAM COMBINING THROUGH THE NONLINEAR RESPONSE OF A STRONGLY DRIVEN ATOMIC TRANSITION



I. Weak-probe-wave Amplification

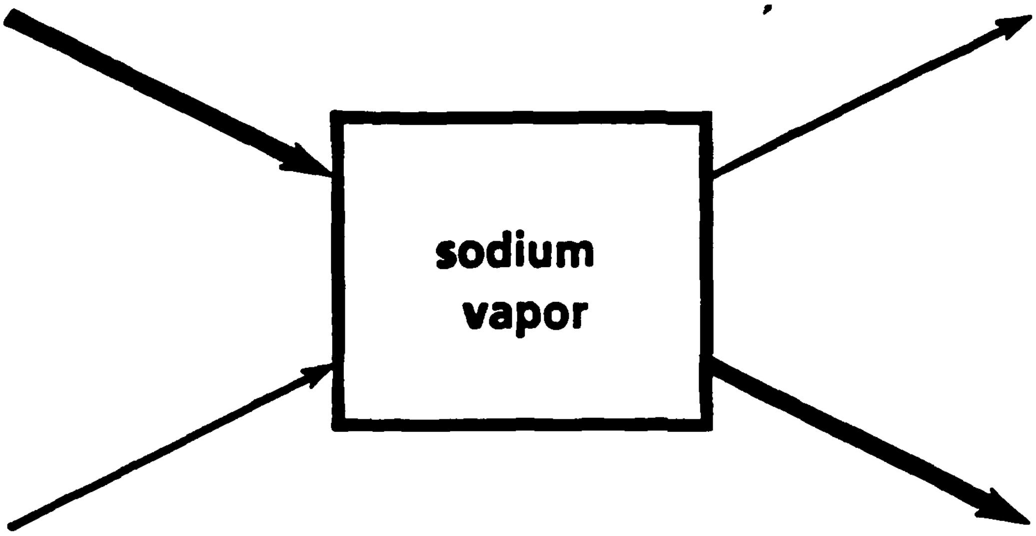
M. T. Gruneisen, K. R. MacDonald, and R. W. Boyd

II. Coupling of Two Intense Beams

A. L. Gaeta, M. T. Gruneisen, K. R. MacDonald, and R. W. Boyd

The Institute of Optics
University of Rochester

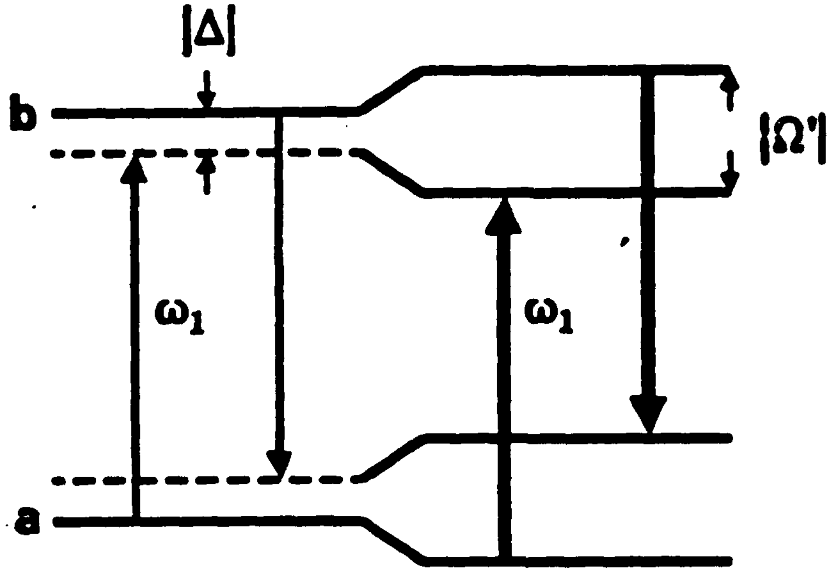
INDUCED GAIN AND MODIFIED ABSORPTION OF A WEAK PROBE BEAM IN A STRONGLY DRIVEN SODIUM VAPOR



- system of two-level atoms
- probe-wave amplification
- 38-fold increase in probe intensity measured
- atomic motion, collisional dephasing

M. T. Gruneisen, K. R. MacDonald, and R. W. Boyd, to be published in J. Opt. Soc. Am. B, January, 1988.

ORIGIN OF SPECTRAL FEATURES: THE AC STARK EFFECT



generalized Rabi frequency $\Omega' = \frac{\Delta}{|\Delta|}[\Omega^2 + \Delta^2]^{1/2}$

SOLUTION TO DENSITY MATRIX EQUATIONS

- Two-level atom
- Pump field treated correctly to all orders
- Probe field treated to only first order

Probe-Wave Absorption Coefficient:

$$\alpha(\delta) = \alpha_o(\rho_{bb} - \rho_{aa})^{dc} \ \mathrm{Im}\left[\frac{(\delta + i/T_1)(\delta - \Delta + i/T_2)(\Delta - i/T_2) - \Omega^2\delta/2}{(\Delta - i/T_2)D(\delta)}\right]$$

$$D(\delta) = (\delta + i/T_1)(\delta + \Delta + i/T_2)(\delta - \Delta + i/T_2) - \Omega^2(\delta + i/T_2)$$

Steady-State Population Inversion:

$$(\rho_{bb} - \rho_{aa})^{dc} = \frac{(1 + \Delta^2 T_2^{\,2})(\rho_{bb} - \rho_{aa})^0}{1 + \Delta^2 T_2^{\,2} + \Omega^2 T_1 T_2}$$

probe-pump detuning $\delta = \omega_3 - \omega_1$

dipole dephasing time T_2

population relaxation time T_1

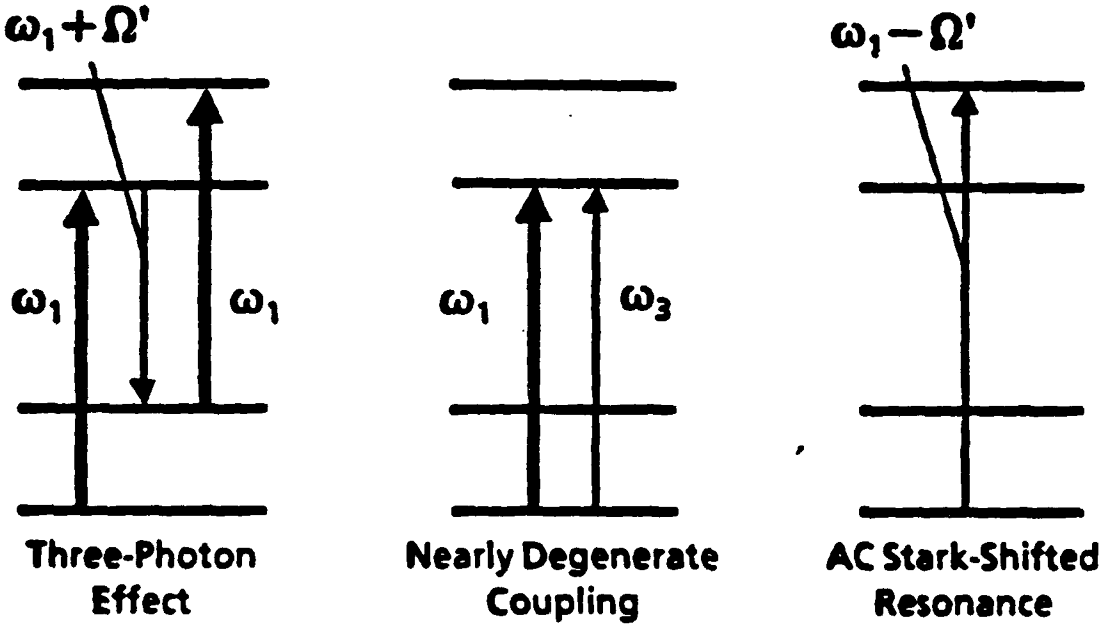
pump-resonance detuning $\Delta = \omega_1 - \omega_{ba}$

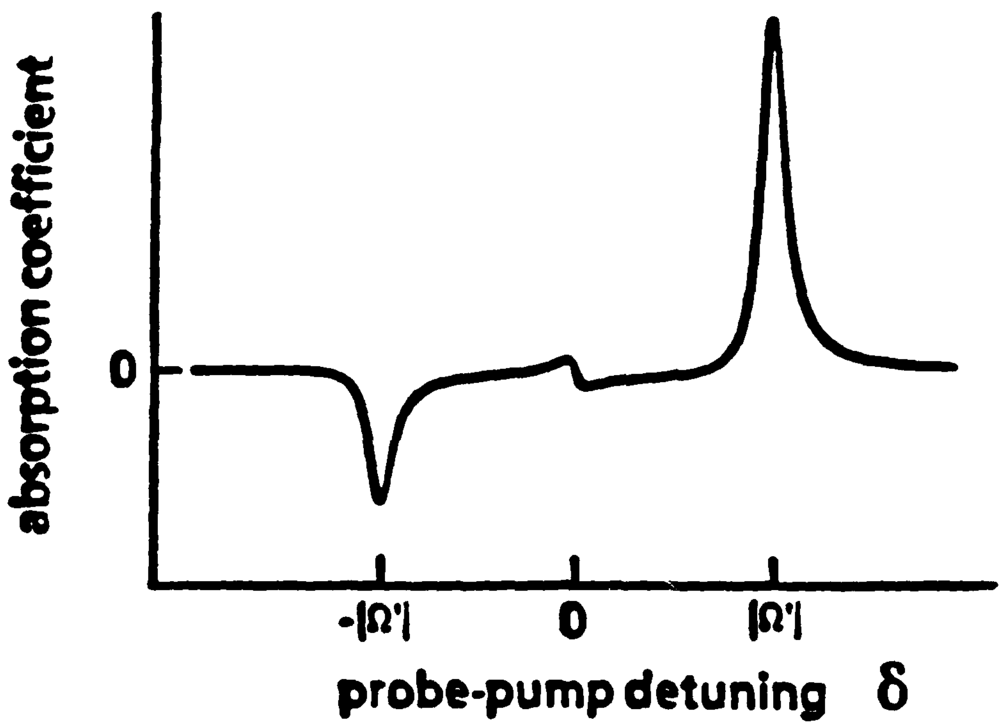
on-resonance Rabi frequency $\Omega = |\mu_{ba}|E_1/\hbar$

B. R. Mollow, Phys. Rev. A 5, 2217 (1972)

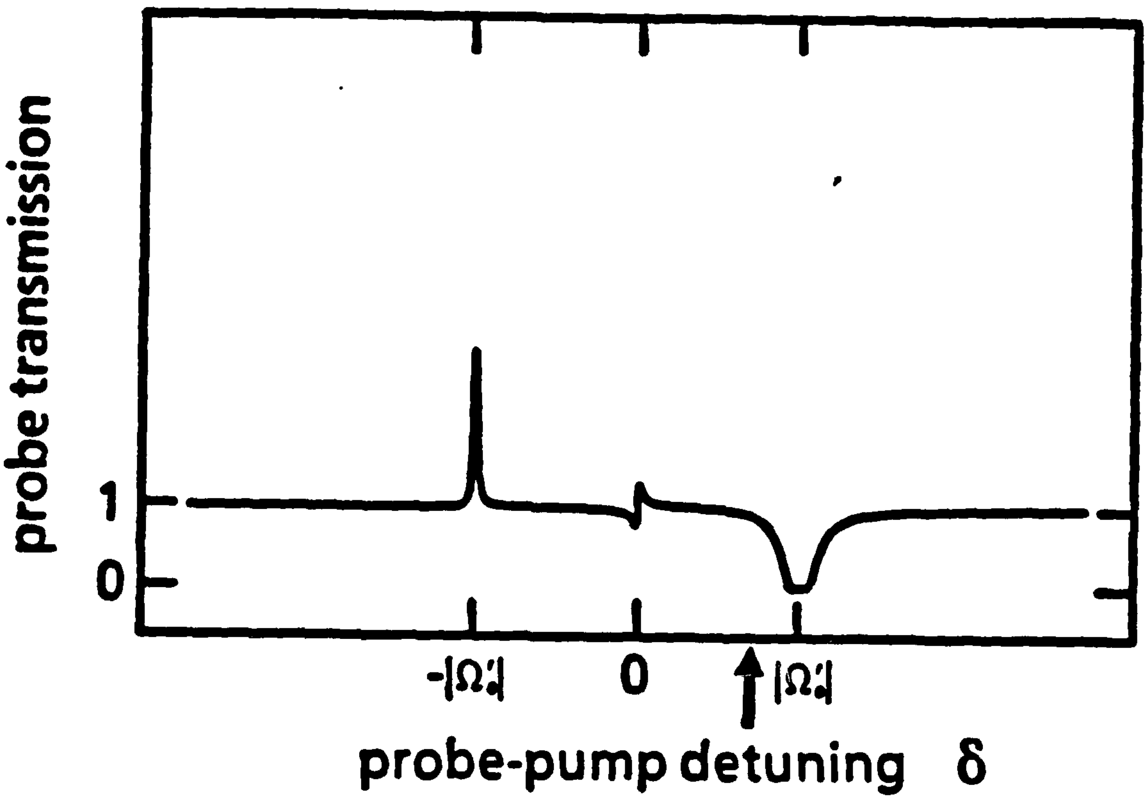
R. W. Boyd, M. G. Raymer, P. Narum, and D. J. Harter, Phys. Rev. A 24, (1981)

INDUCED GAIN AND MODIFIED ABSORPTION OF A WEAK PROBE WAVE





PROBE TRANSMISSION SPECTRUM: COLLECTION OF STATIONARY ATOMS

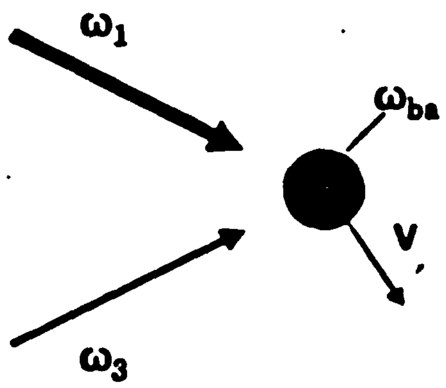


Ω = 1.2 GHz $\quad T_2/T_1$ = .28

Δ = -1.3 GHz $\quad \alpha_0 L$ = 300

F. Y. Wu, S. Ezekiel, M. Ducloy, B. R. Mollow, Phys. Rev. Lett. 38, 1077 (1977)

EFFECTS OF ATOMIC MOTION ON SINGLE-ATOM RESPONSE



- In general, both $\Delta = \omega_1 - \omega_{ba}$ and $\delta = \omega_3 - \omega_1$ are velocity dependent.

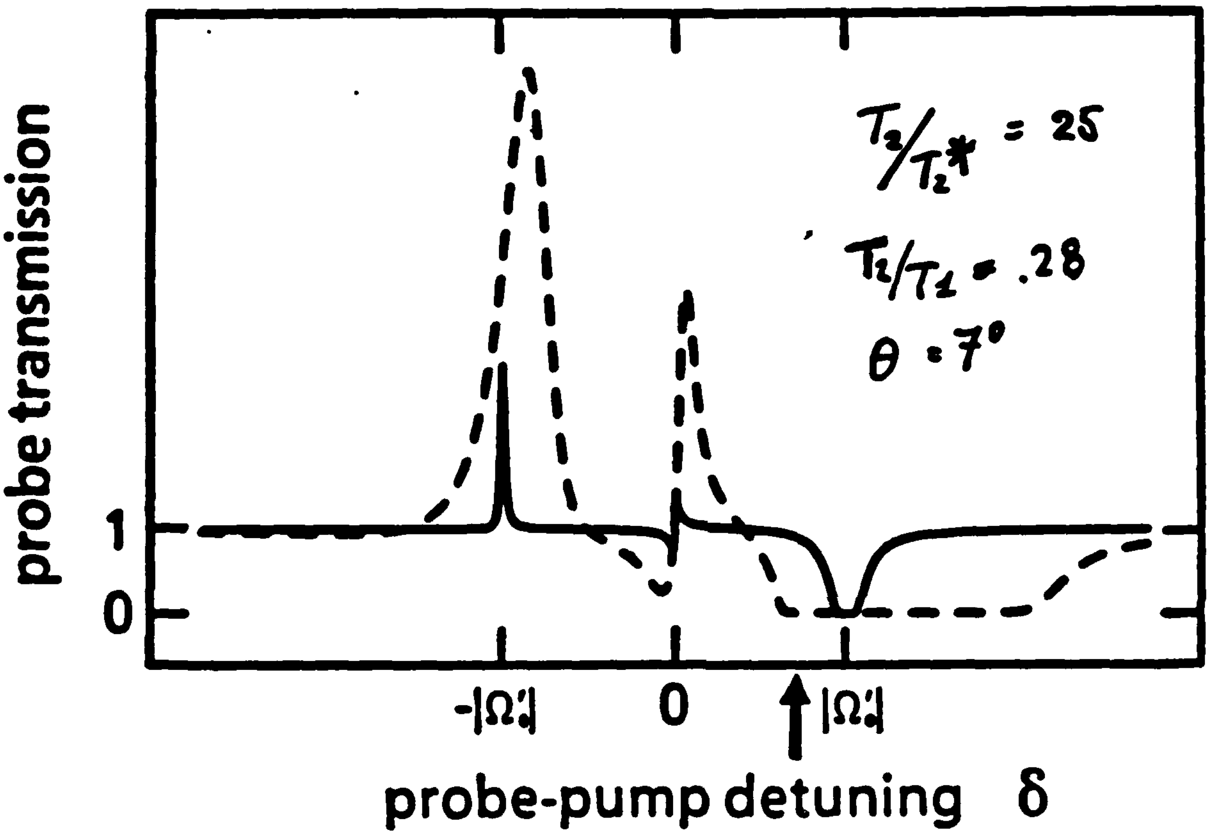
- Doppler shift in Δ introduces velocity dependence in Ω'.

- For copropagating waves, there is no Doppler shift in $\delta = \omega_3 - \omega_1$.

__General Expression for Amplitude Absorption Coefficient__:

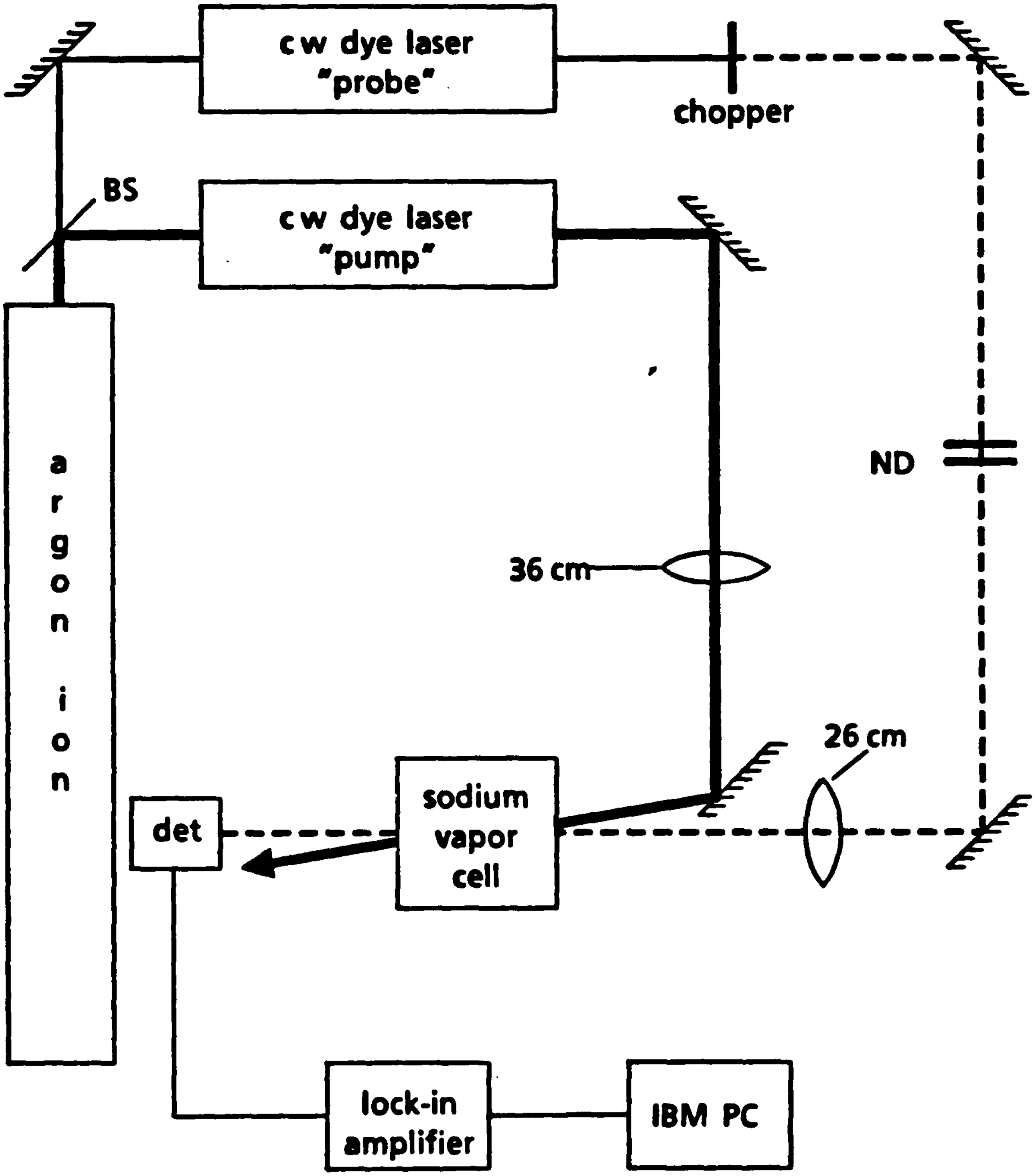
$$\alpha^D(\omega_3,\omega_1) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} \iiint_{-\infty}^{+\infty} d^3\mathbf{v}\ \alpha(\omega_3 + \mathbf{k}_3\cdot\mathbf{v},\ \omega_1 + \mathbf{k}_1\cdot\mathbf{v})\ \exp\left(-\frac{m|\mathbf{v}|^2}{2k_B T}\right)$$

PROBE TRANSMISSION SPECTRUM WITH DOPPLER BROADENING

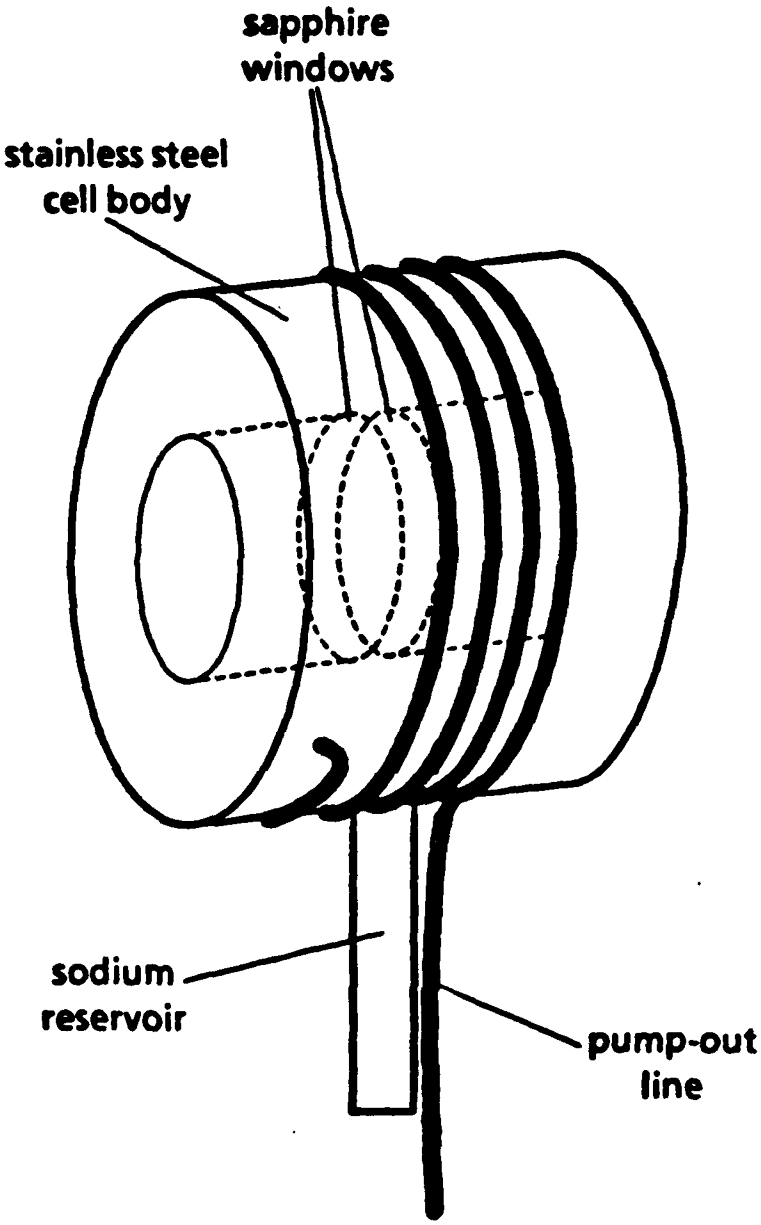


- Three-photon resonance is broadened to Doppler width.
- Three-photon resonance peak is "pulled" towards pump frequency.
- For nearly copropagating waves, the nearly degenerate lineshape remains narrow and increases in amplitude.

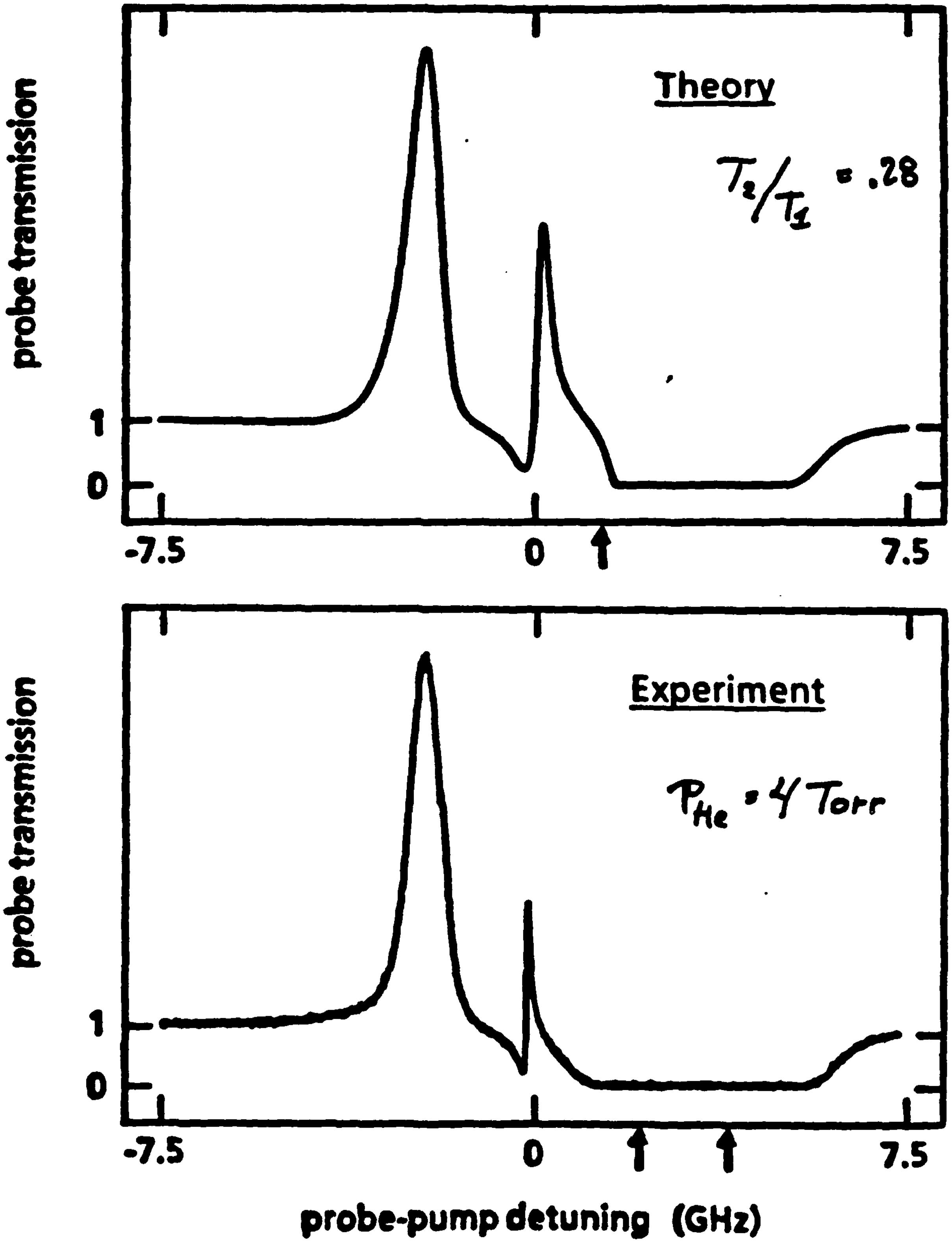
EXPERIMENTAL CONFIGURATION



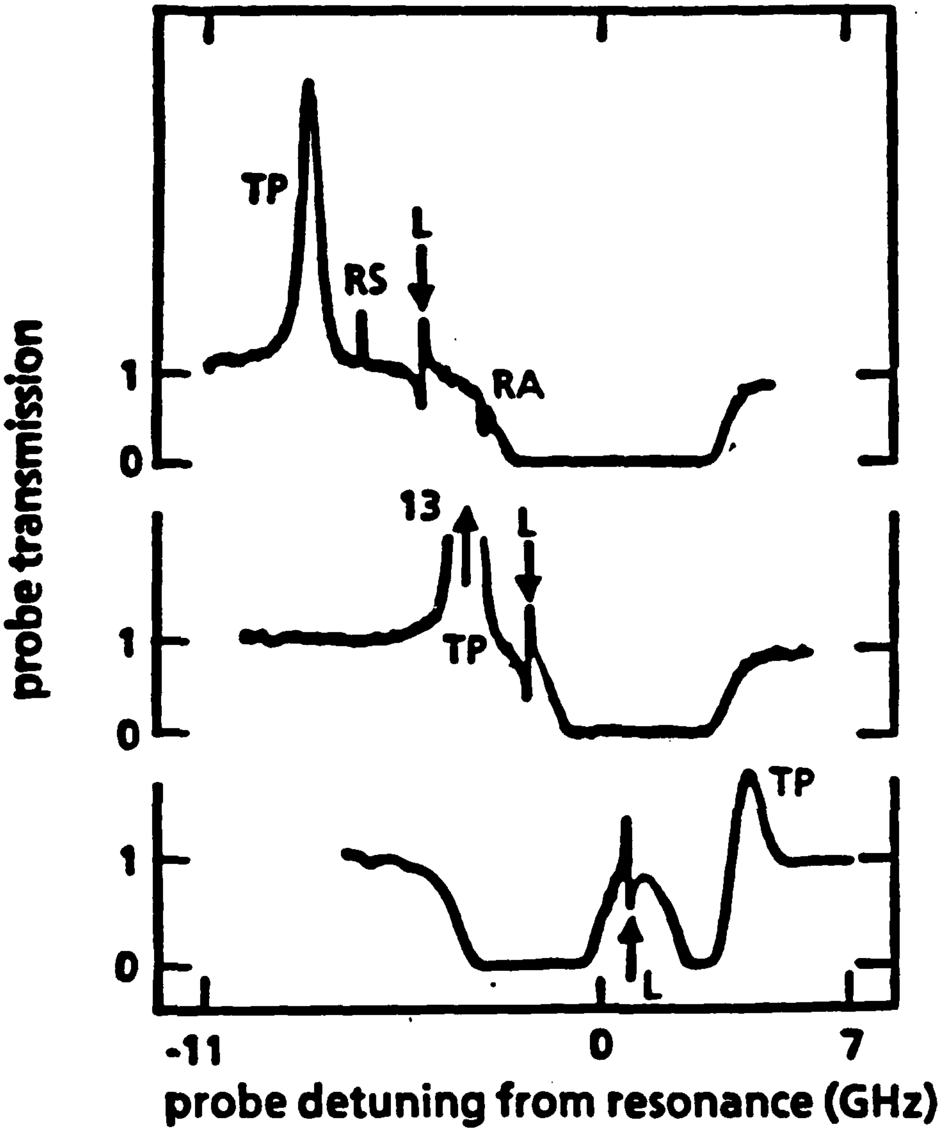
SODIUM VAPOR CELL



TRANSMISSION SPECTRA WITH DOPPLER BROADENING

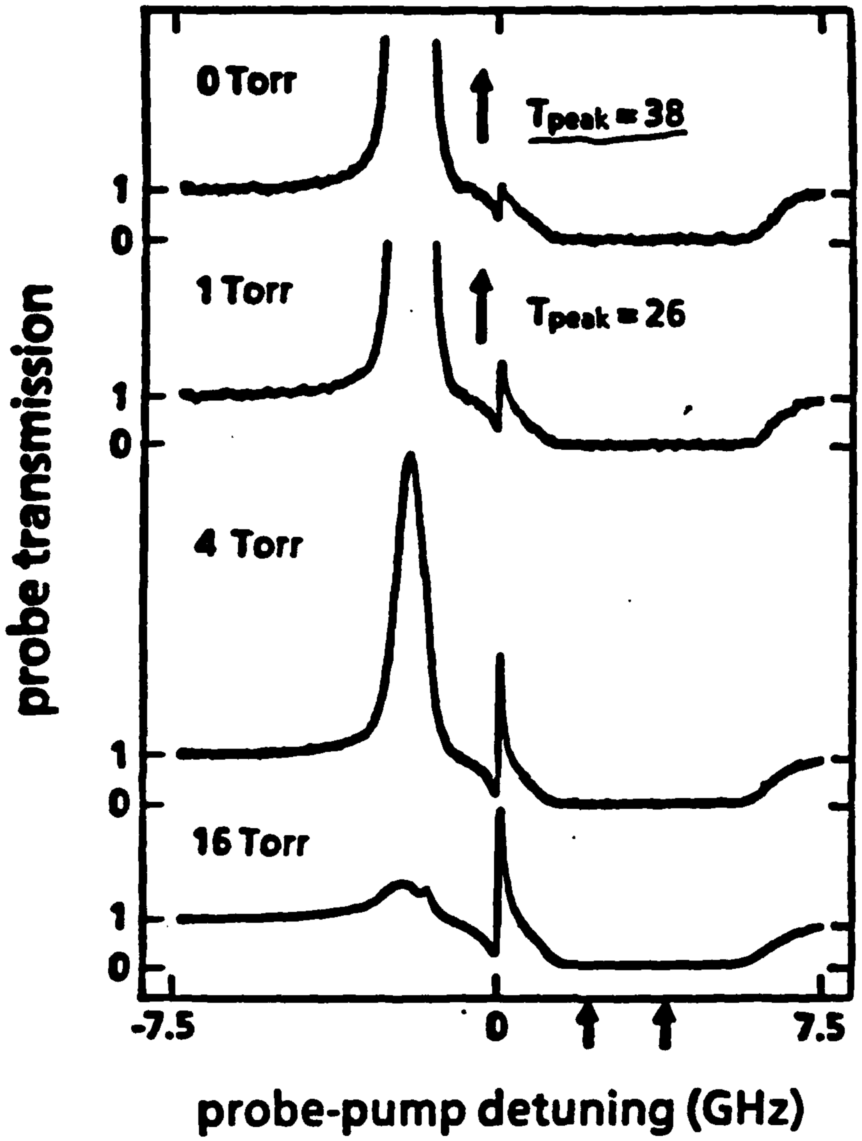


EFFECTS OF PUMP-LASER DETUNING



- Raman scattering from ground state hyperfine levels observed.
- Amplitude and location of three-photon peak vary with Δ.
- sign of a_{nd} and Ω' depend on sign of Δ.

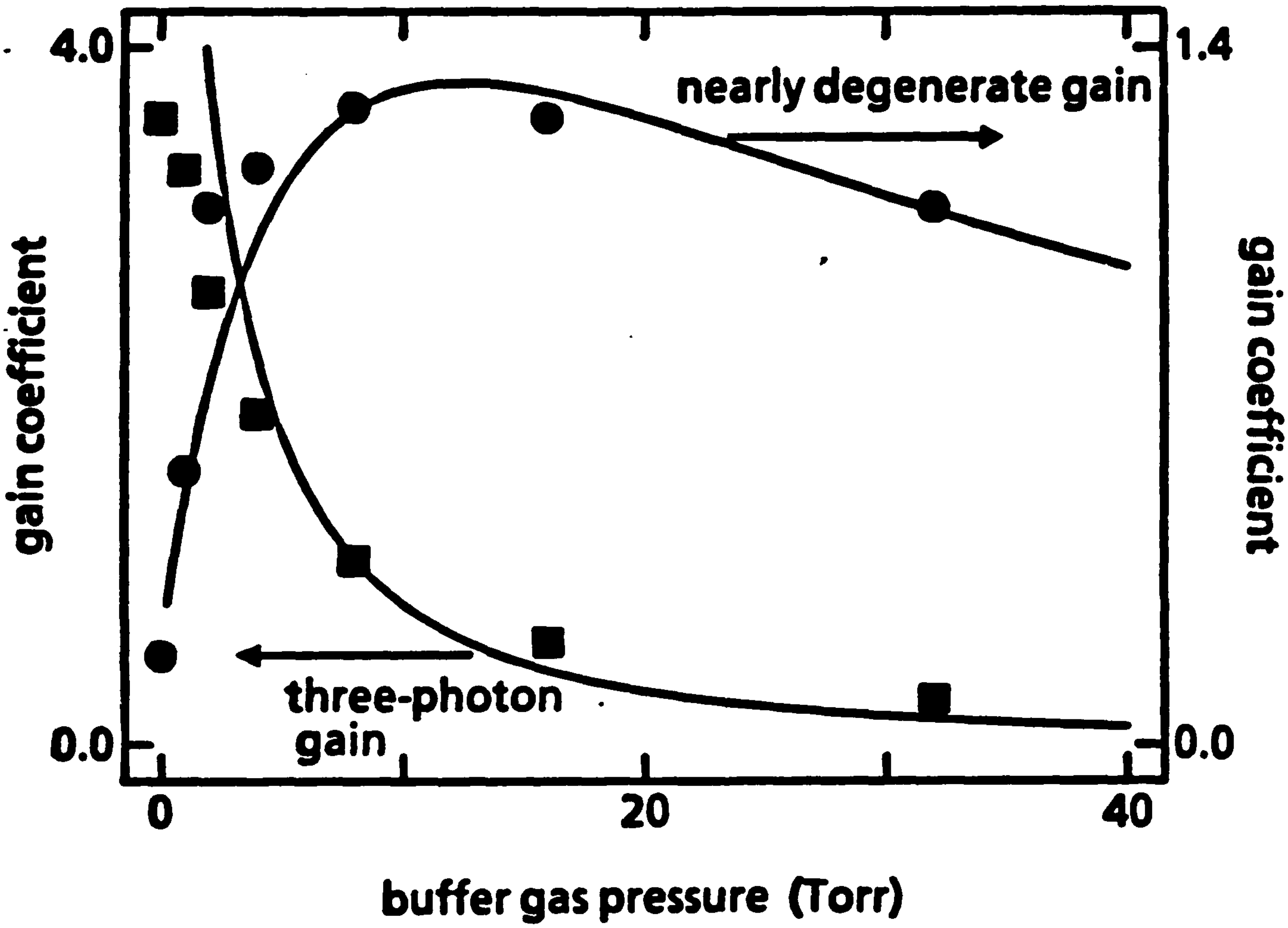
EFFECTS OF COLLISIONAL DEPHASING



- Three-photon resonance diminishes rapidly with increased collisional dephasing.

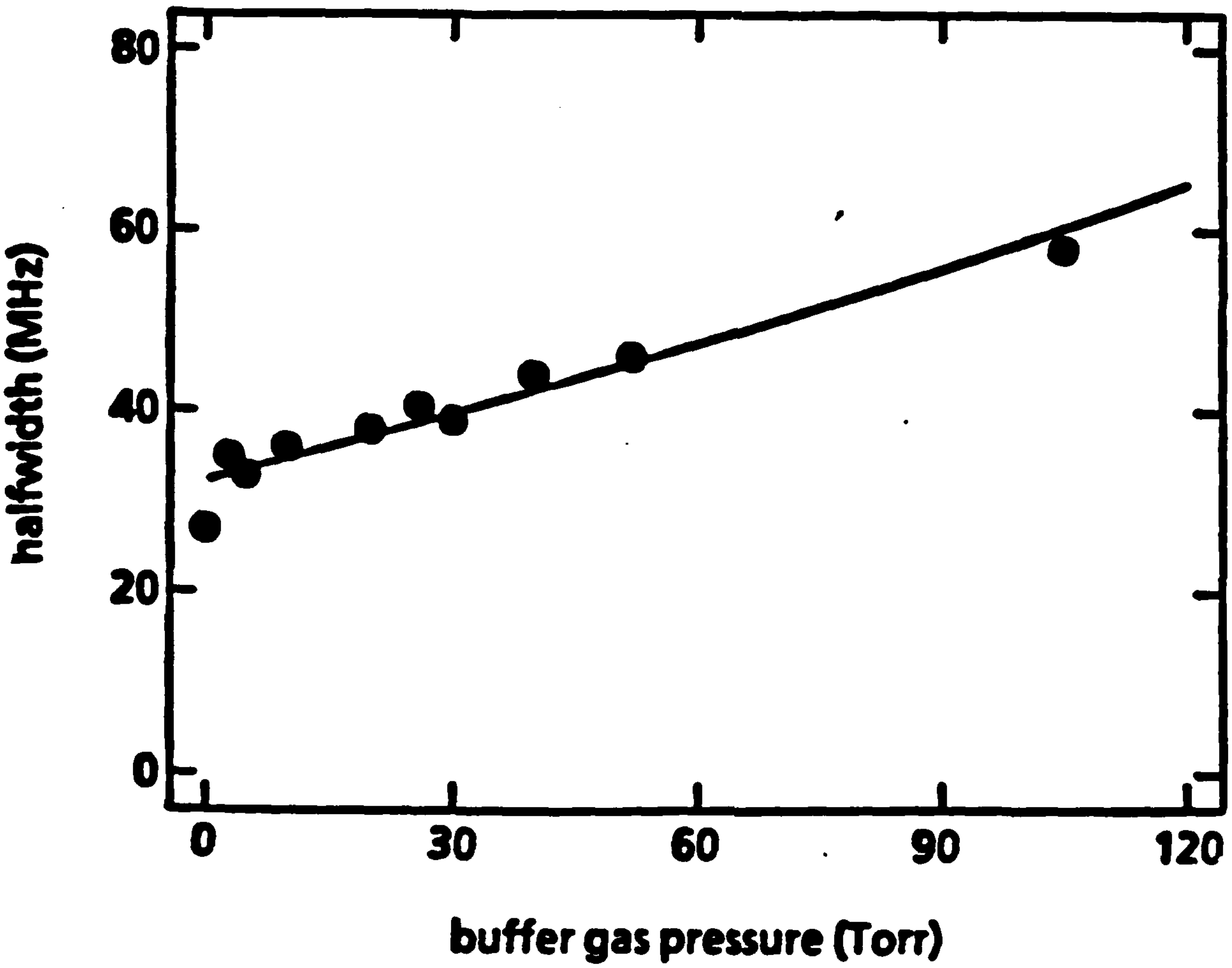
- Amplitude of nearly degenerate resonance can be enhanced by collisional dephasing.

GAIN VS BUFFER GAS PRESSURE



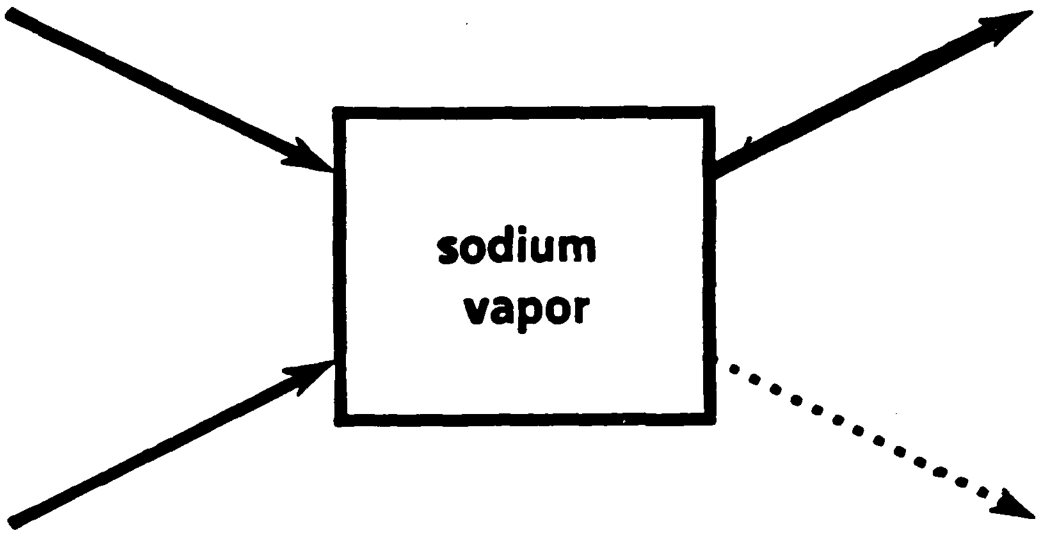
- Peak Three-photon gain occurs for zero buffer gas pressure.
- Nearly degenerate gain can be optimized by adding buffer gas.
- Single two-level atom theory can be used to describe functional dependence.

WIDTH OF NEARLY DEGENERATE RESONANCE
VS
BUFFER GAS PRESSURE



- At zero pressure, width is broadened to 30 MHz by atomic motion.
- width is broadened additionally by collisional dephasing.

LASER BEAM COMBINING IN SODIUM VAPOR



- Two-level atom
- propagation effects, atomic motion
- Limited coupling efficiency via three-photon effect
- High efficiency coupling at nearly degenerate feature

CONTINUED FRACTION SOLUTION TO OPTICAL BLOCH EQUATIONS*

Strong field absorption coefficient:

$$\alpha_2 = D_2\{\alpha - [Re(\kappa) - (\delta\omega + \gamma)T_2 Im(\kappa)]I_1\}$$

where

$$\alpha = \frac{\alpha_0}{1 + D_1(I_1 + I_2) - 2|I_c|^2 Re\{K_0 L_1 F\}}$$

and

$$\kappa = L_1 F \alpha$$

with

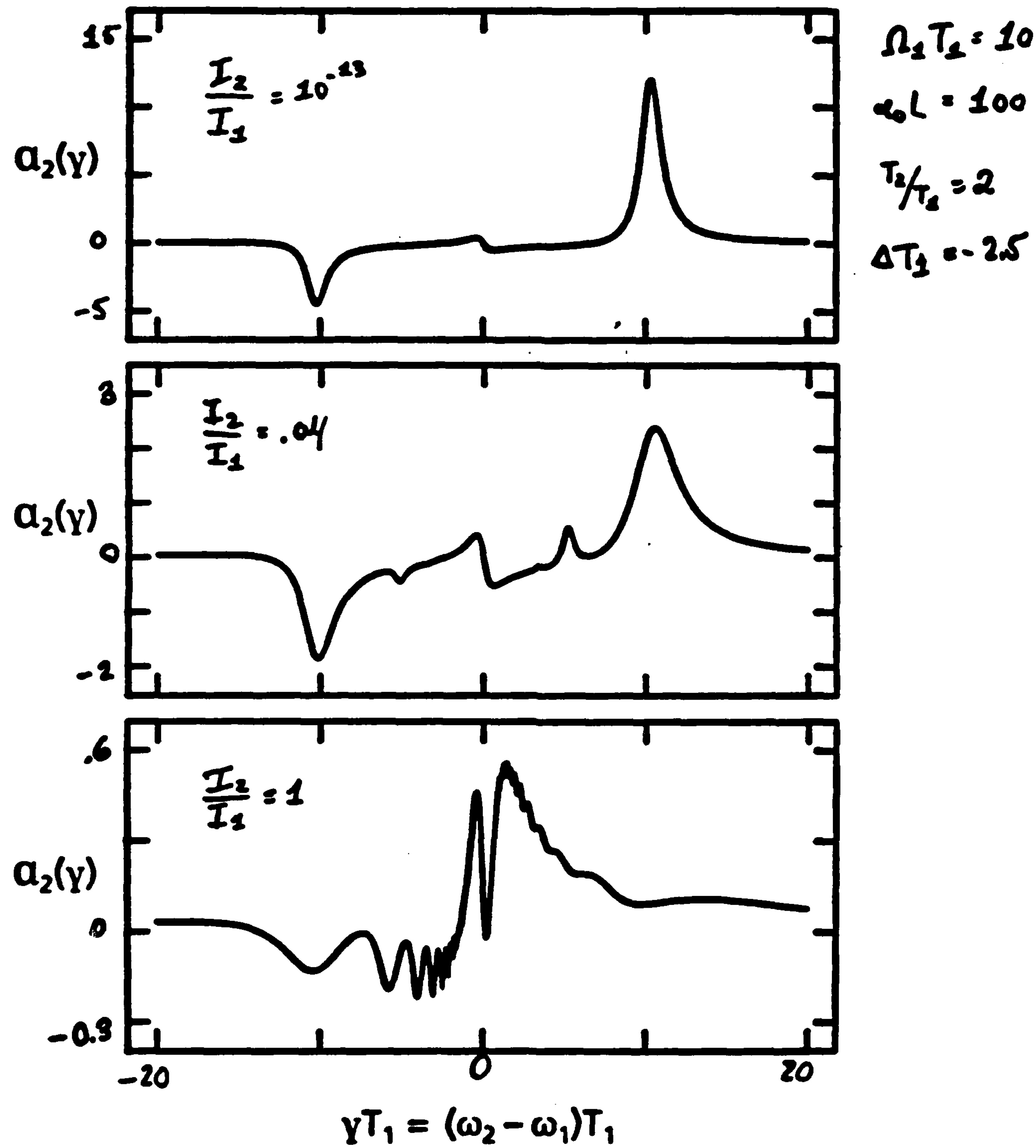
$$= \cfrac{1}{1 + M_1 I_1 + N_1 I_2 - i\gamma T_1 - \cfrac{K_1 L_2 |I_c|^2}{1 + M_2 I_1 + N_2 I_2 - i2\gamma T_1 + \cfrac{K_2 L_3 |I_c|^2}{1 + M_3 I_1 + N_3 I_2 - i3\gamma T_1 - \cfrac{K_3 L_4 |I_c|^2}{1 + M_4 \cdots}}}}$$

A. L. Gaeta, unpublished

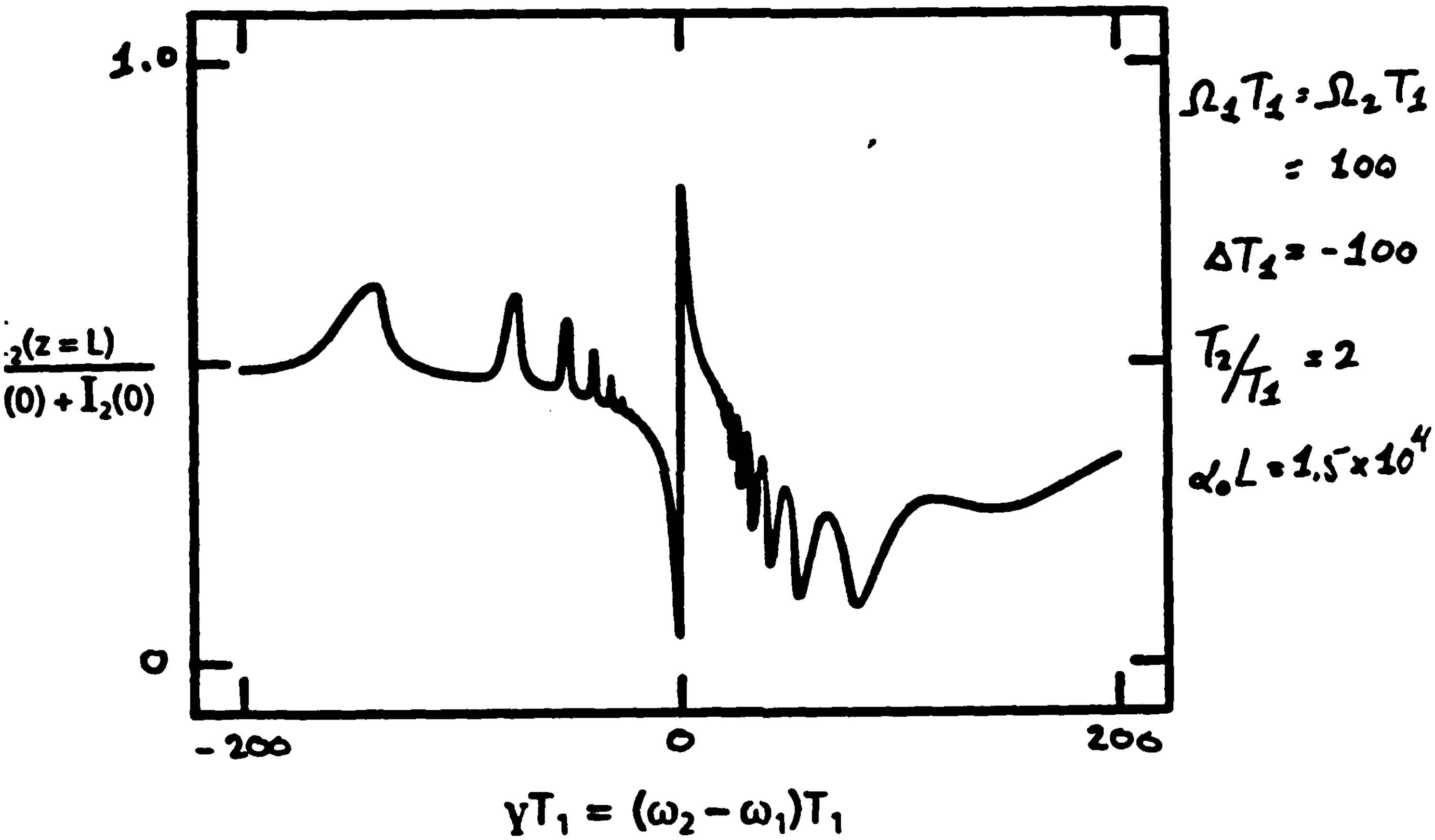
L. W. Hillman, J. Krasinski, K. Koch, and C. R. Stroud, J. Opt. Soc. Am. B 2, 211 (1985)

G. S. Agarwal and N. Nayak, J. Opt. Soc. Am. B 1, 164 (1984)

INTENSE FIELD ABSORPTION SPECTRUM



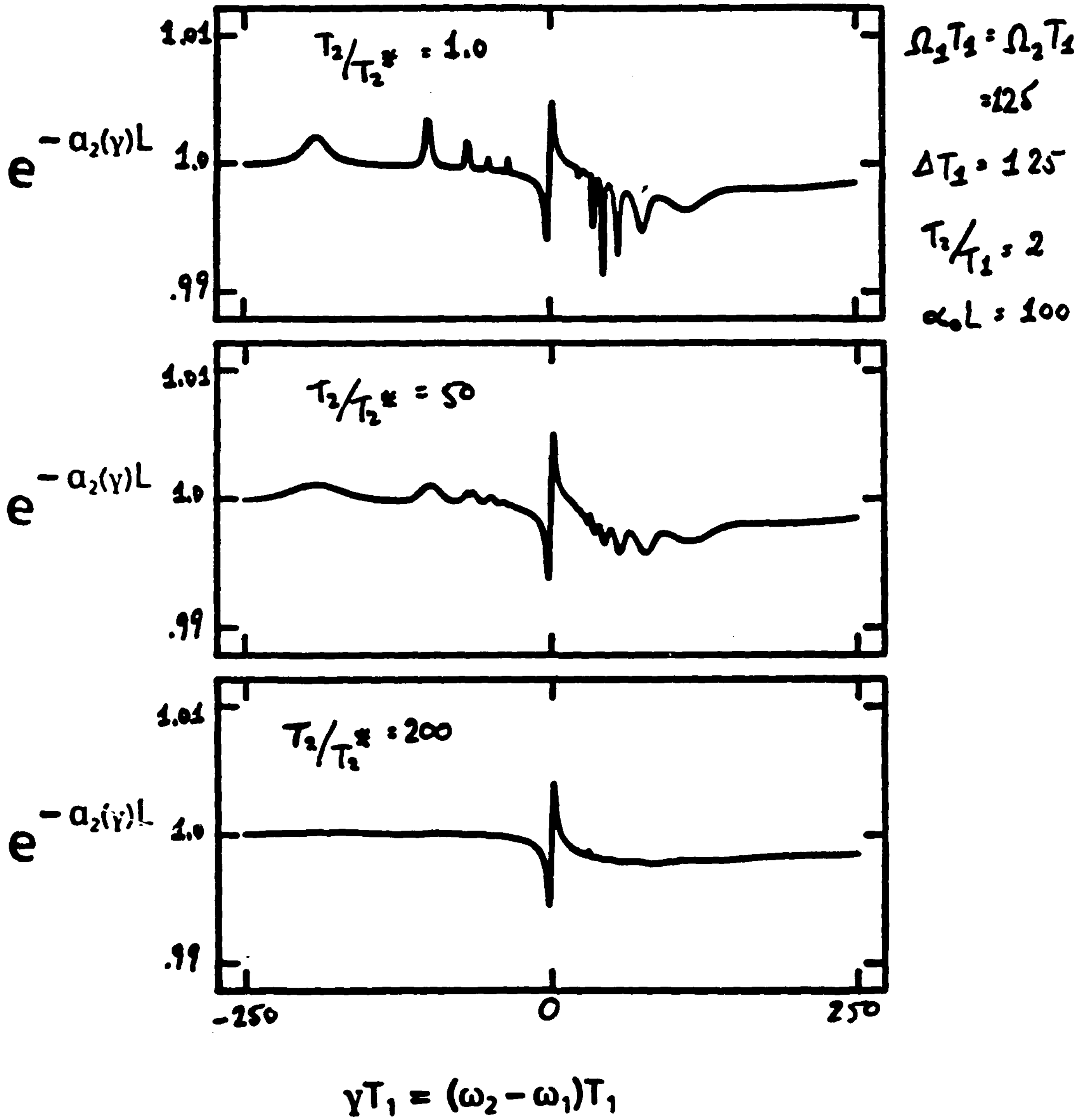
TRANSMISSION SPECTRUM WITH PROPAGATION EFFECTS



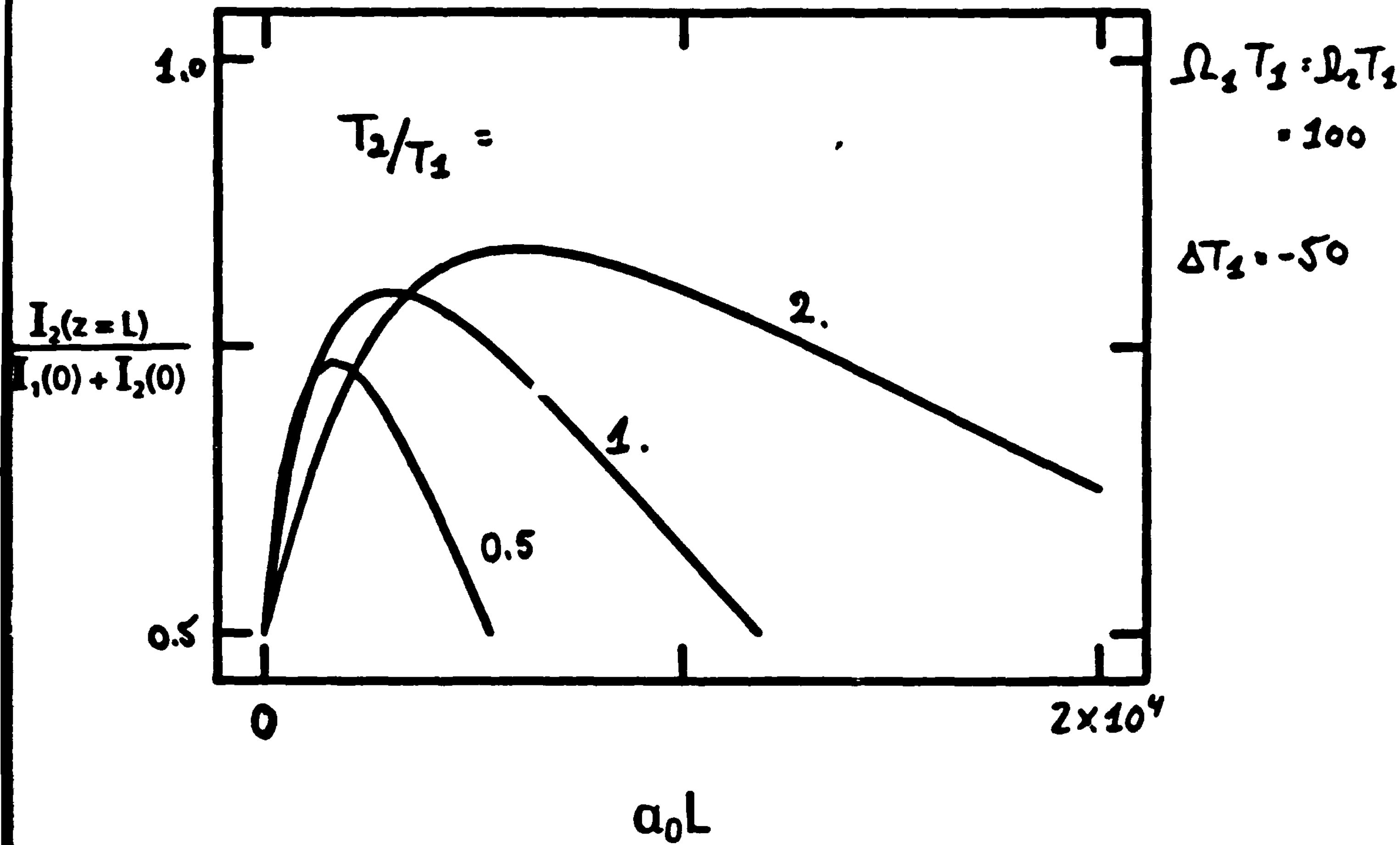
- Define coupling efficiency: $0 \leq \frac{I_1(z=L)}{I_1(0) + I_2(0)} \leq 1$
- Nearly degenerate feature provides most efficient coupling.
- Three-photon coupling is limited by:
  1. propagation – Ω' changes due to depletion.
  2. excitation – scattering process requires two pump photons.

EFFECTS OF DOPPLER BROADENING

- Neglect propagation effects

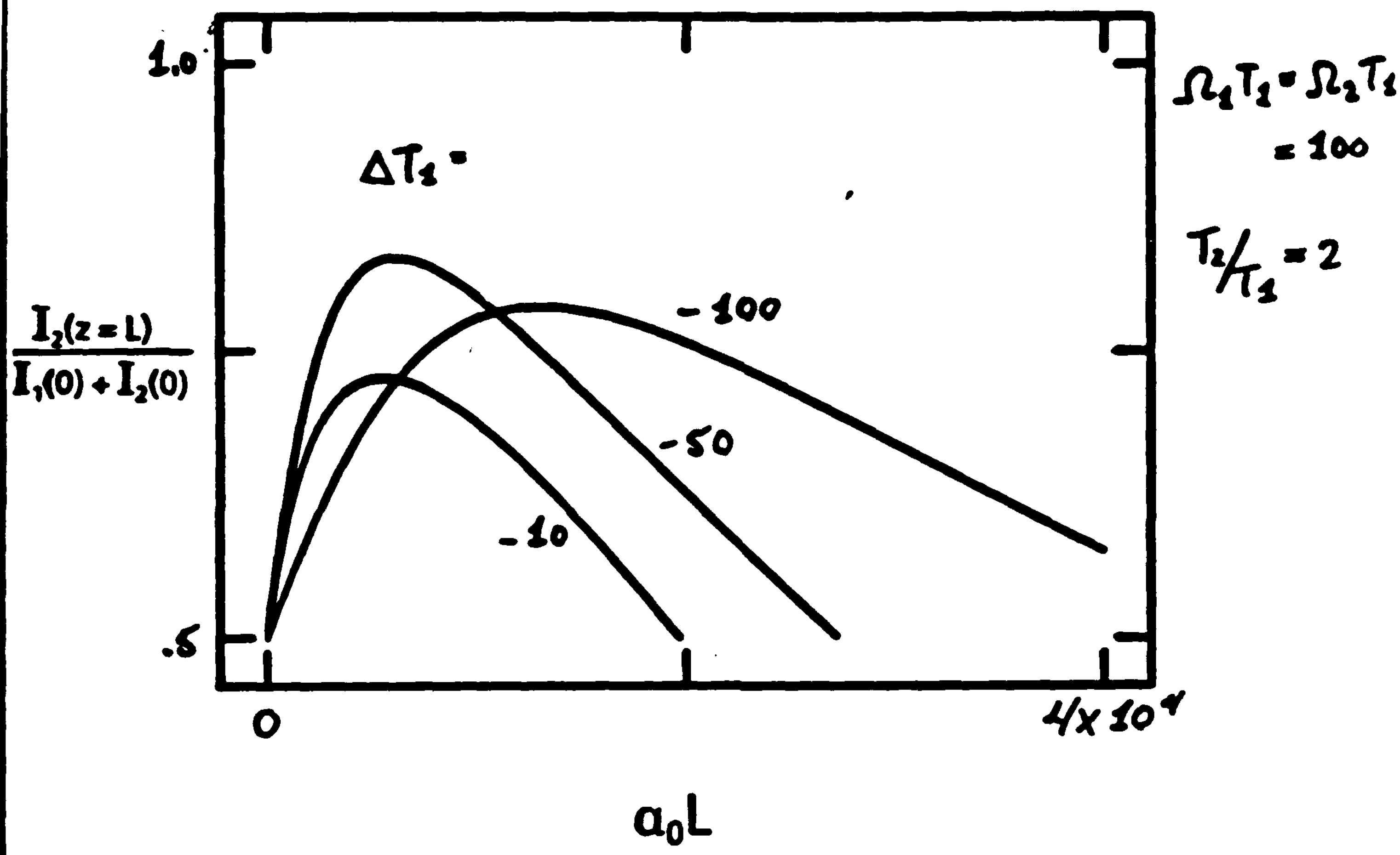


NEARLY DEGENERATE COUPLING
EFFECTS OF COLLISIONAL DEPHASING



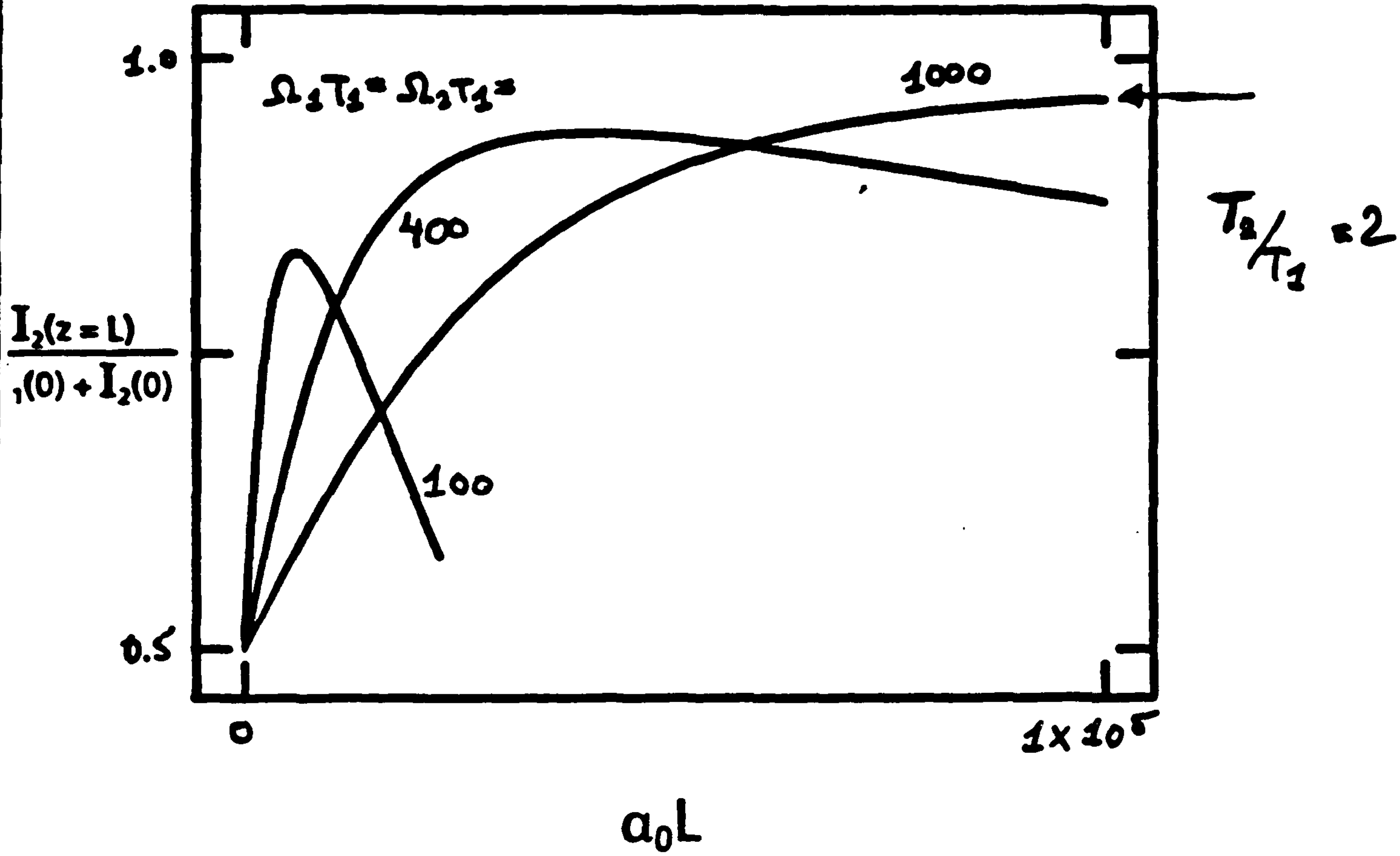
- At low a_0L, choose $T_2/T_1 < 2.0$
- At high a_0L, choose $T_2/T_1 = 2.0$

NEARLY DEGENERATE COUPLING
EFFECTS OF DETUNING



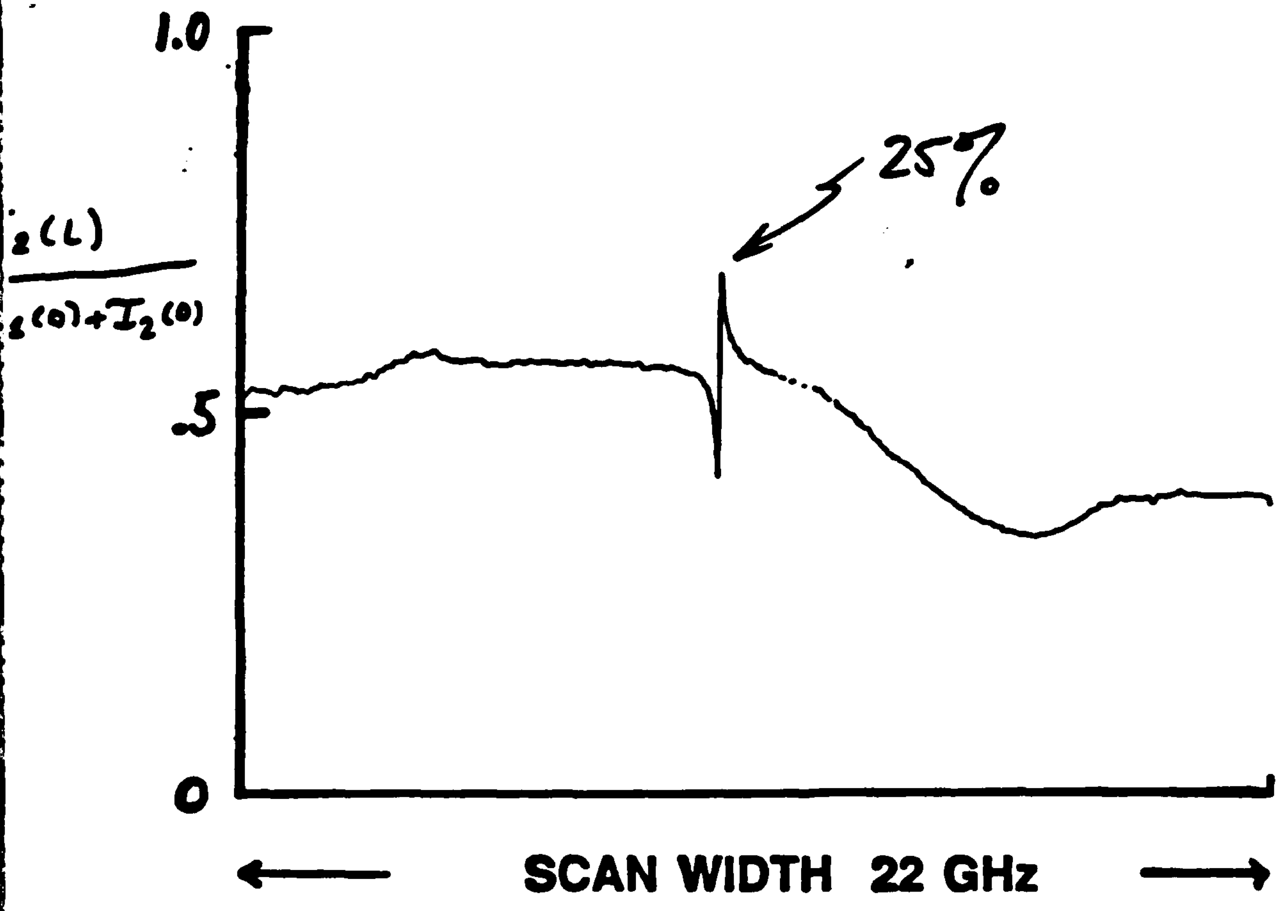
- For low $a_0 L$, tune near resonance.
- For large $a_0 L$, tune away from resonance to avoid absorption losses.
- Choose $\Delta = \Omega/2$ to optimize coupling.

NEARLY DEGENERATE COUPLING
EFFECTS OF LASER INTENSITY



- High coupling efficiency requires: $T_2/T_1 = 2.0$
  $a_0 L > 10^5$
  $\Omega_1 T_1 > 10^3$

BEAM COMBINING DATA



$I_1 = 450\ \mathrm{W/cm^2} \Rightarrow \Omega_1 T_1 = 380$

$I_2 = 600\ \mathrm{W/cm^2} \Rightarrow \Omega_2 T_2 = 435$

$T = 230°\mathrm{C}$

$N \approx 10^{13}/\mathrm{cm}^3$

$P_{He} = 10$ Torr

$\alpha_0 L \approx 10^3$

SUMMARY

Part I: probe beam amplification

I. Observed probe wave amplification in a strongly driven atomic vapor

- A. Three-photon effect
  1. measured large amplification: G = 38
  2. gain diminishes rapidly with collisional dephasing
- B. Nearly Degenerate Coupling
  1. measured amplification of G = 4 at P_{He} = 10 Torr
  2. feature is "robust" in presence of collisional dephasing

II. Theoretical modeling

- A. Stationary two-level atom theory accurately models gain dependence on buffer gas pressure
- B. Numerical average over a Maxwell velocity distribution accounts for effects of atomic motion

Part II: beam combining

I. Treated analytically by continued fractions

- A. Three-photon effect
  1. diminishes with Doppler broadening
  2. propagation effects reduce coupling efficiency
  3. coupling efficiency is inherently limited
- B. Nearly degenerate resonance
  1. insensitive to Doppler broadening (copropagating waves)
  2. large coupling efficiencies are possible

II. Experimental results

- A. 20% energy transfer measured to date 25%
  1. intensity limited
  2. experiment in progress

CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
APPLICATIONS OF PHASE CONJUGATION

CENTER FOR NIGHT VISION AND ELECTRO-OPTICS

OPTICAL PHASE CONJUGATION IN PHOTOREFRACTIVE MATERIALS

LASER RESEARCH TEAM: R & D of nonlinear optical materials, techniques, and concepts

- O Beam Control Devices
  - o Optical Switches
  - o Optical Isolators
  - o Filters
- O Laser Compcnents
  - o New Sources
  - o Q–Switches
  - o Modulators

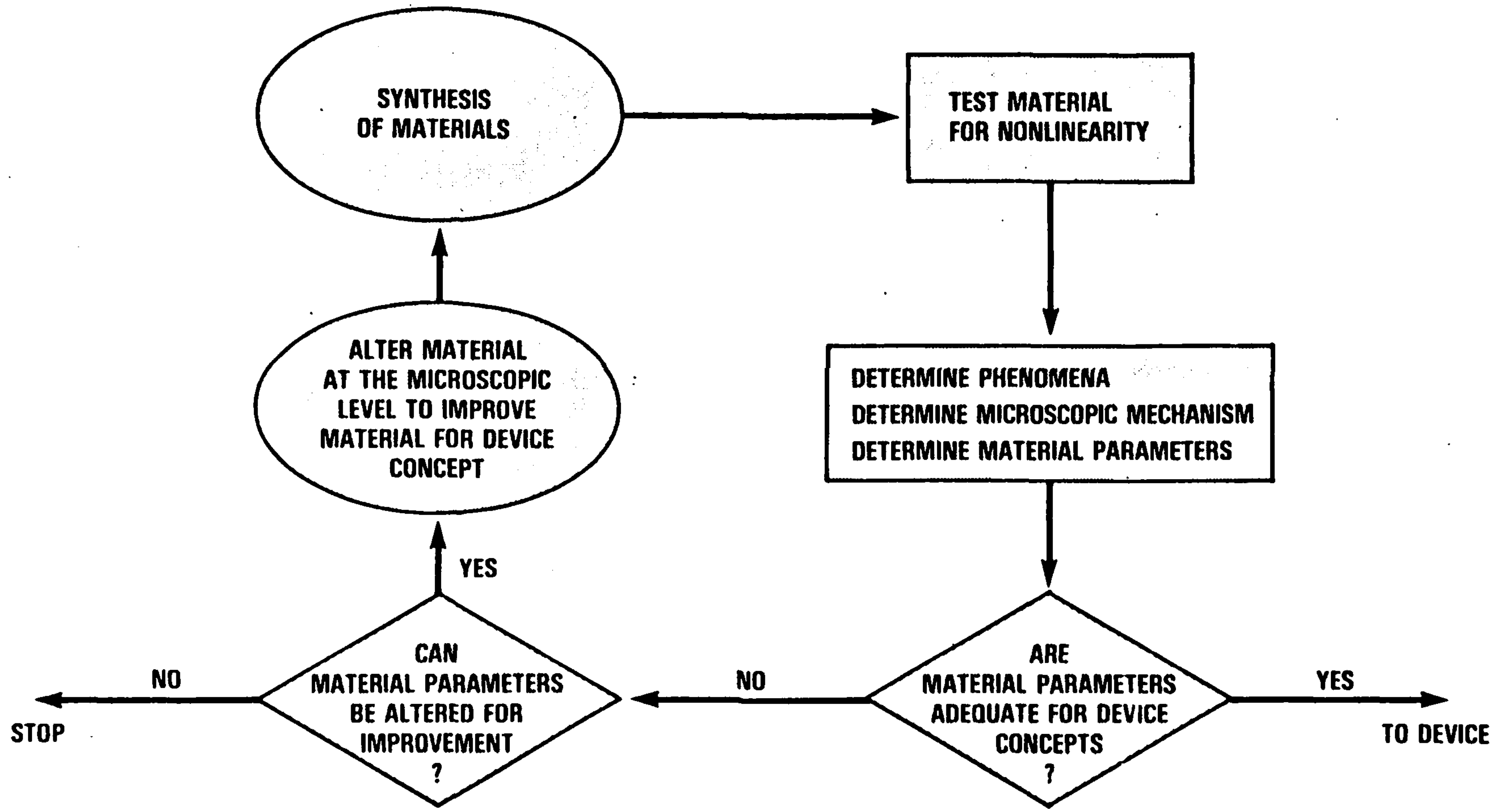
RECENT RESEARCH ACTIVITY

- O Tungsten–Bronze Family of Ferroelectric Crystals (SBN & BSKNN)
  - o Ferroelectric Properties (Sensors)
  - o Electro–Optic Properties (Broad–Band Modulators)
  - o Photorefractive Properties
    - – Optical Isolation of Coherent Beams Via Beam Fanning and Two–Beam Coupling
    - – Phase Conjugation for Image Processing (Amplification, Storage, and Enhancement)

KEY ISSUES

- TIME RESPONSE
- SENSITIVITY
- SPECTRAL BANDWIDTH
- MATERIAL AVAILABILITY/QUALITY
- MATERIAL IMPROVEMENTS
- POSSIBILITY FOR NEW DEVICES

NONLINEAR OPTICAL MATERIALS EFFORT



"WONDERS"

- Δn is large ($\sim 10^{-3}$)
- Δn depends on energy and not on intensity
- time to acheive Δn depends on intensity

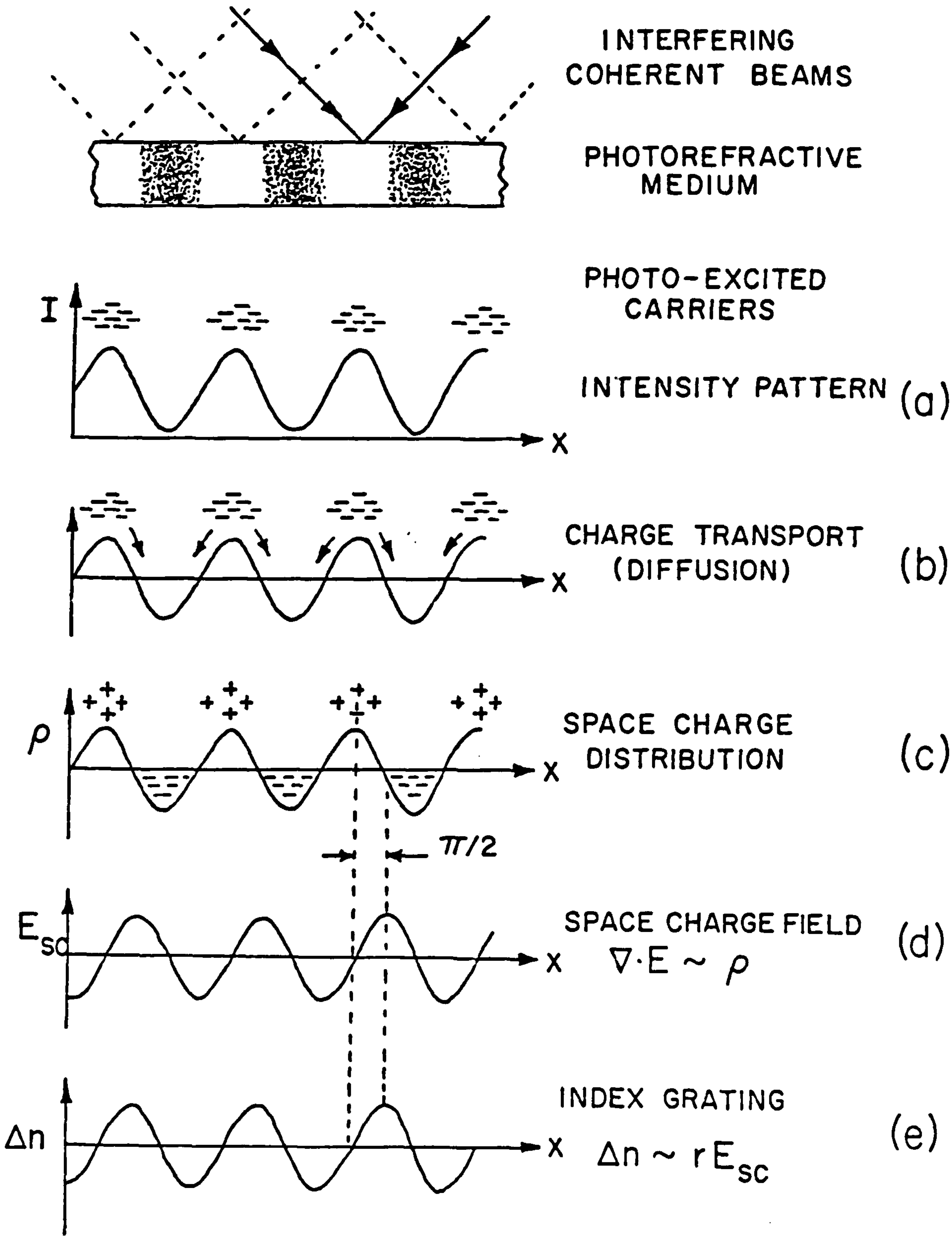
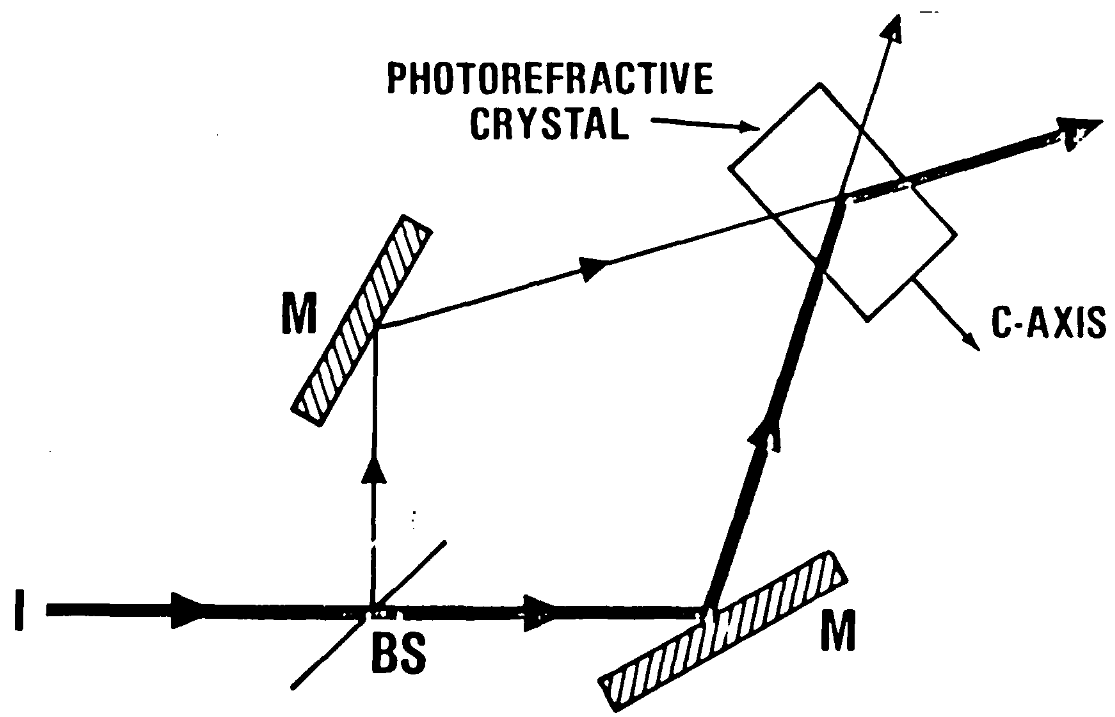

INTERFERING COHERENT BEAMS
PHOTOREFRACTIVE MEDIUM
PHOTO-EXCITED CARRIERS
I
INTENSITY PATTERN
(a)
x
CHARGE TRANSPORT (DIFFUSION)
(b)
x
ρ
SPACE CHARGE DISTRIBUTION
(c)
x
π/2
E_{sc}
SPACE CHARGE FIELD
$\nabla \cdot E \sim \rho$
(d)
x
INDEX GRATING
Δn
$\Delta n \sim r E_{sc}$
(e)
x

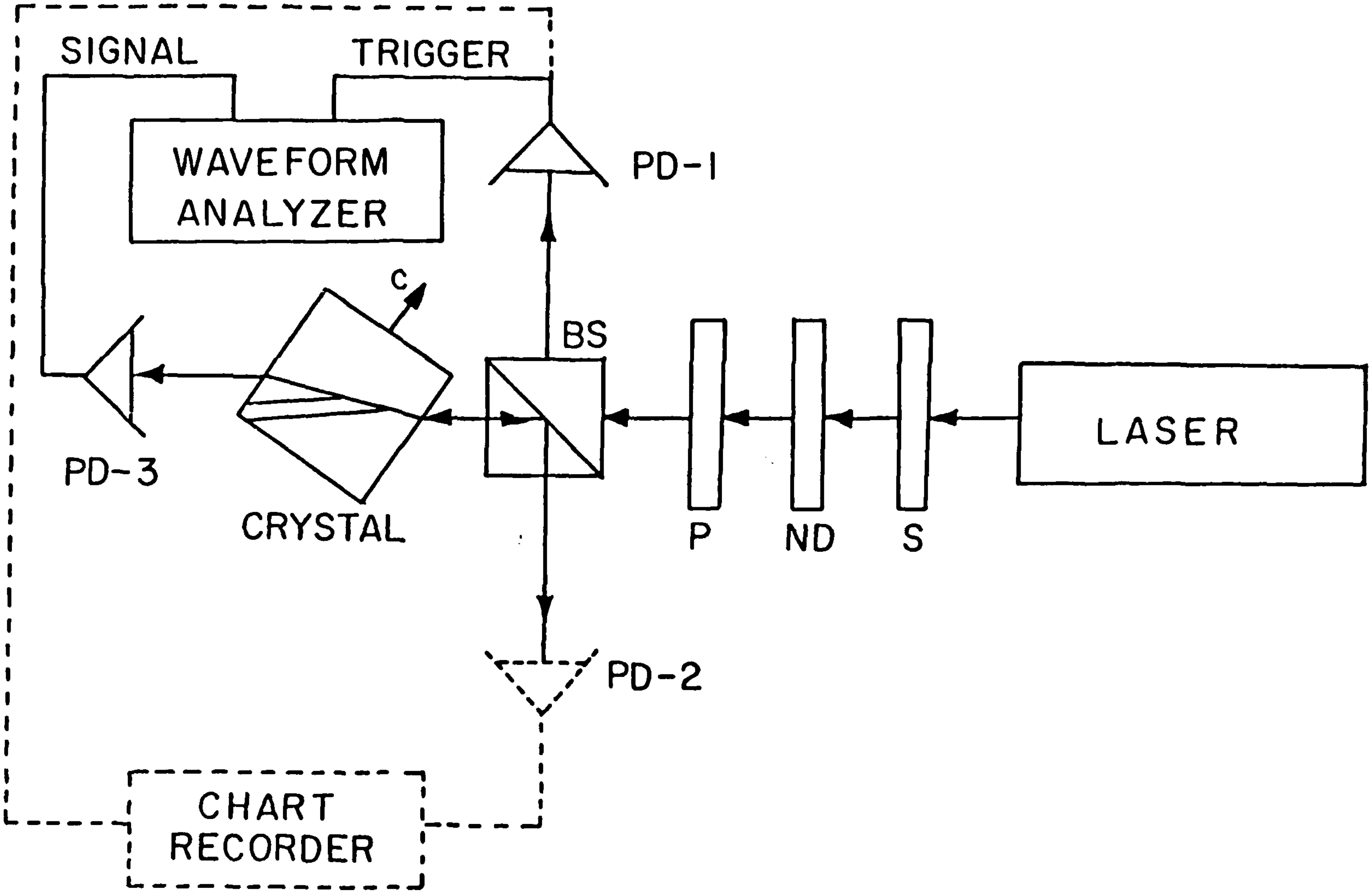
Fig 1

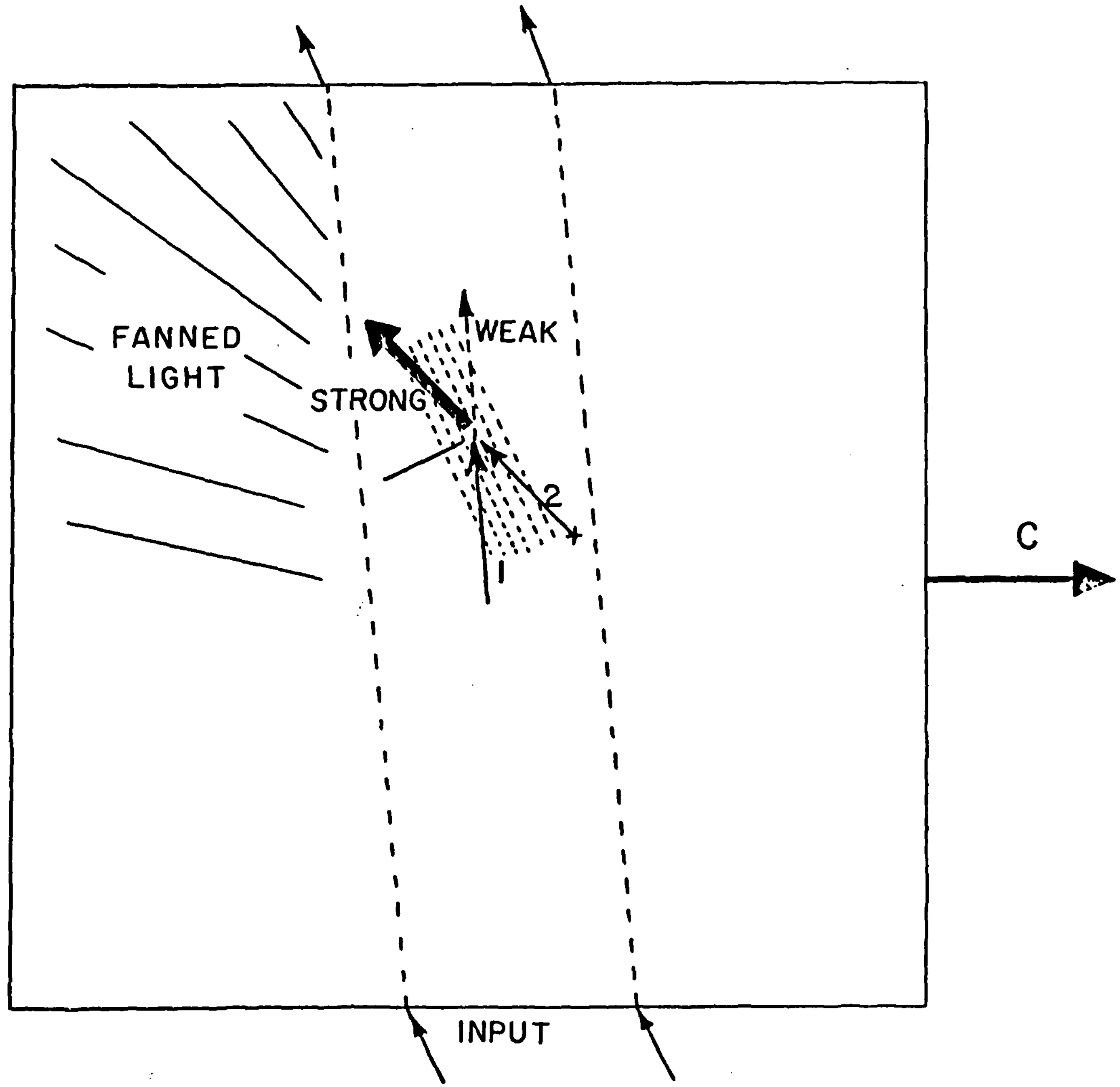
TWO BEAM COUPLING

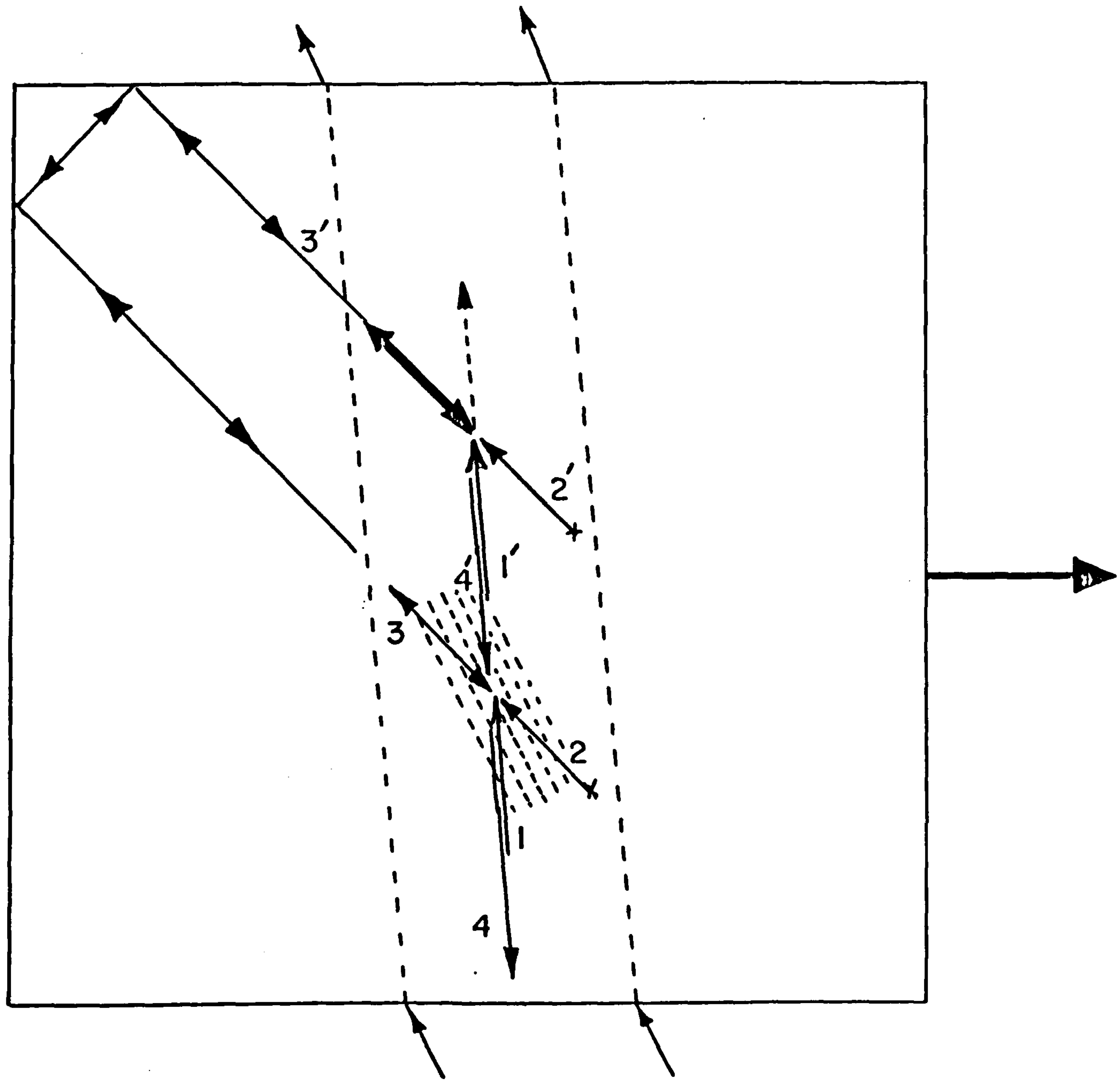


KEY FEATURES:
- LARGE INDEX CHANGES FOR MILLIWATT BEAMS
- INDEX GRATING IS SHIFTED 90° WITH RESPECT TO THE INTENSITY INTERFERENCE PATTERN

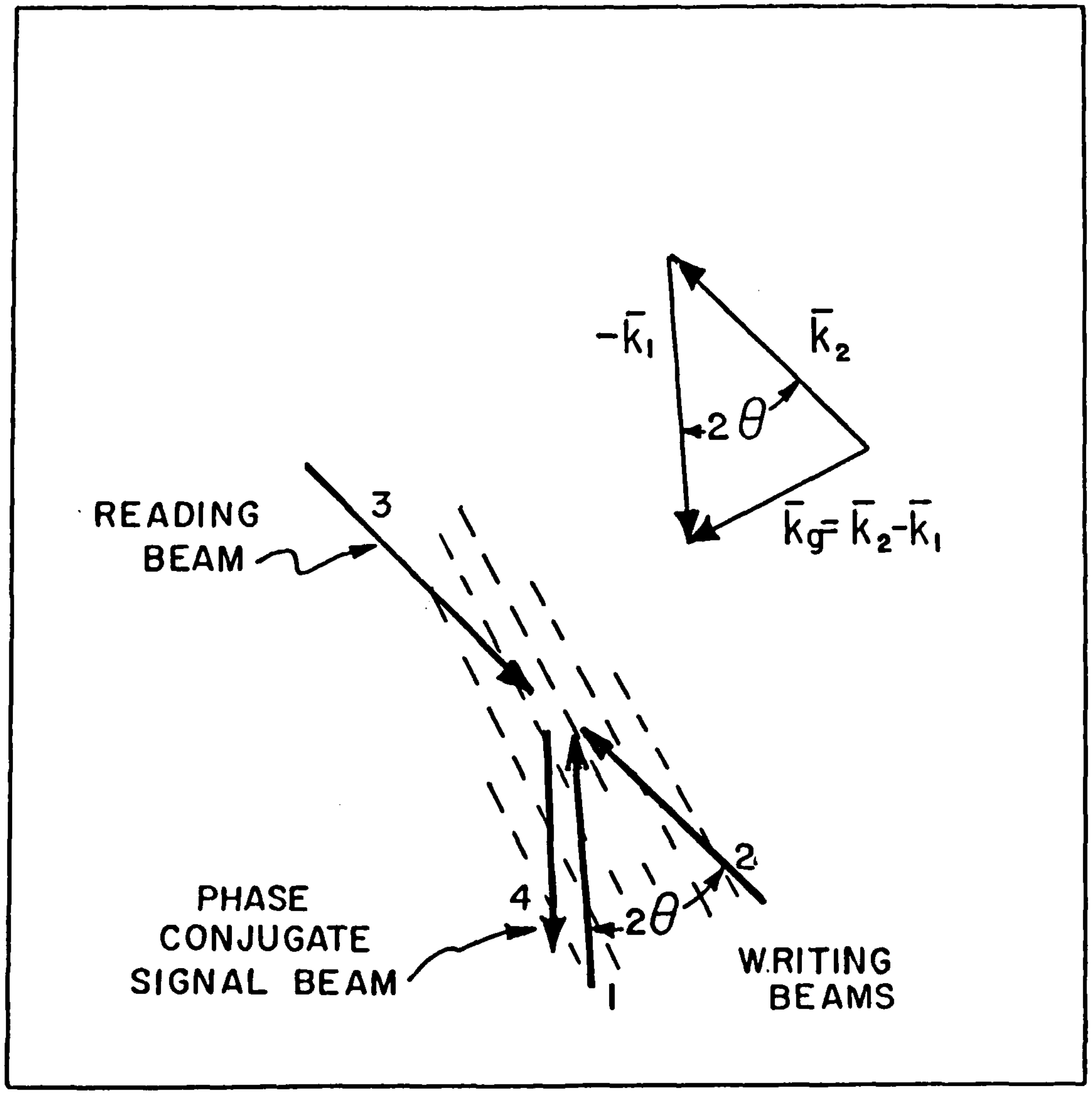
THERefore: STRONG ENERGY EXCHANGE BETWEEN THE TWO BEAMS CAN OCCUR IN THE CRYSTAL SO THAT A WEAK BEAM CAN BE AMPLIFIED AT THE EXPENSE OF A STRONG BEAM


SIGNAL
TRIGGER
WAVEFORM ANALYZER
PD-1
c
BS
PD-3
CRYSTAL
LASER
P
ND
S
PD-2
CHART RECORDER

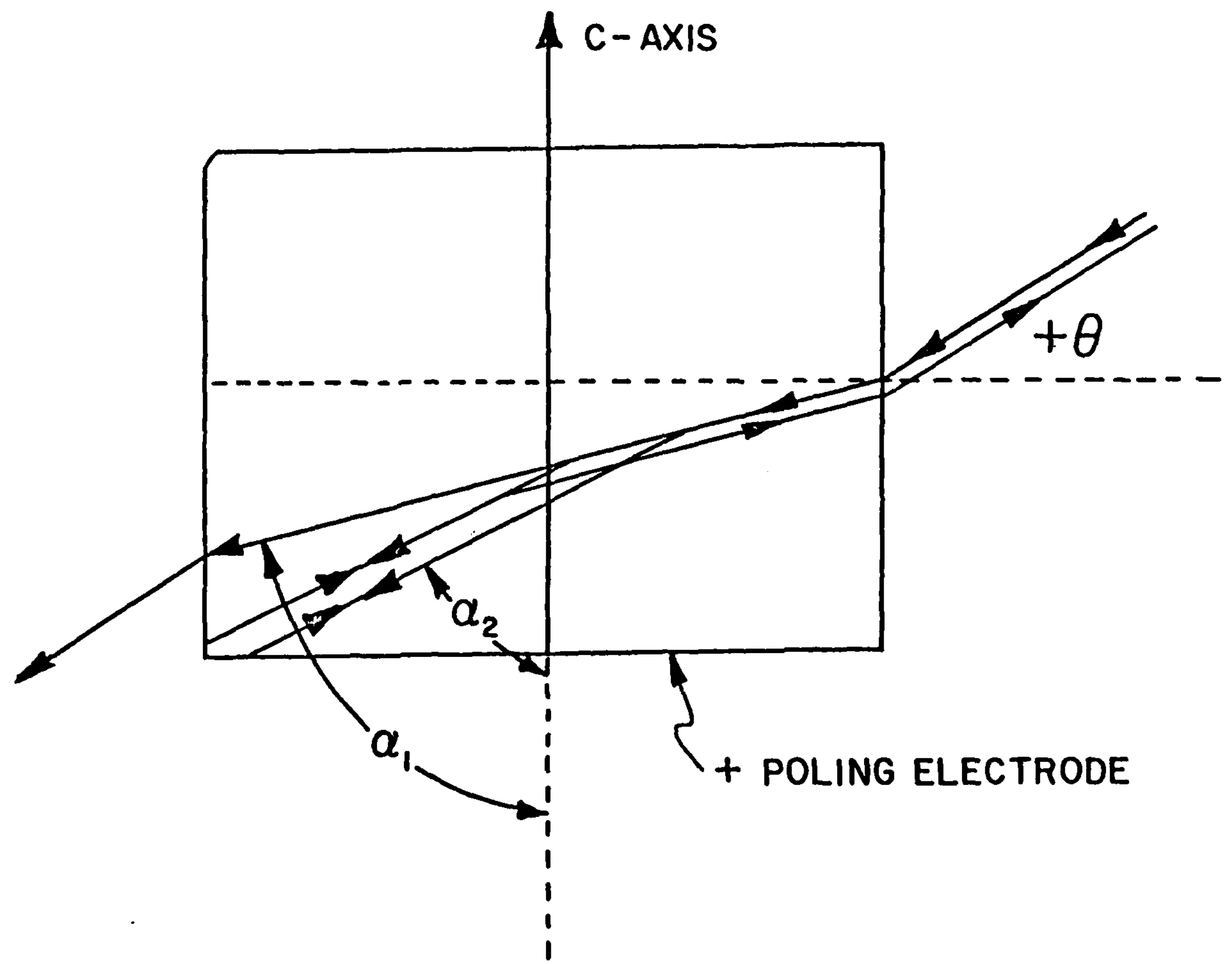

C
FANNED
LIGHT
WEAK
STRONG
2
1
INPUT

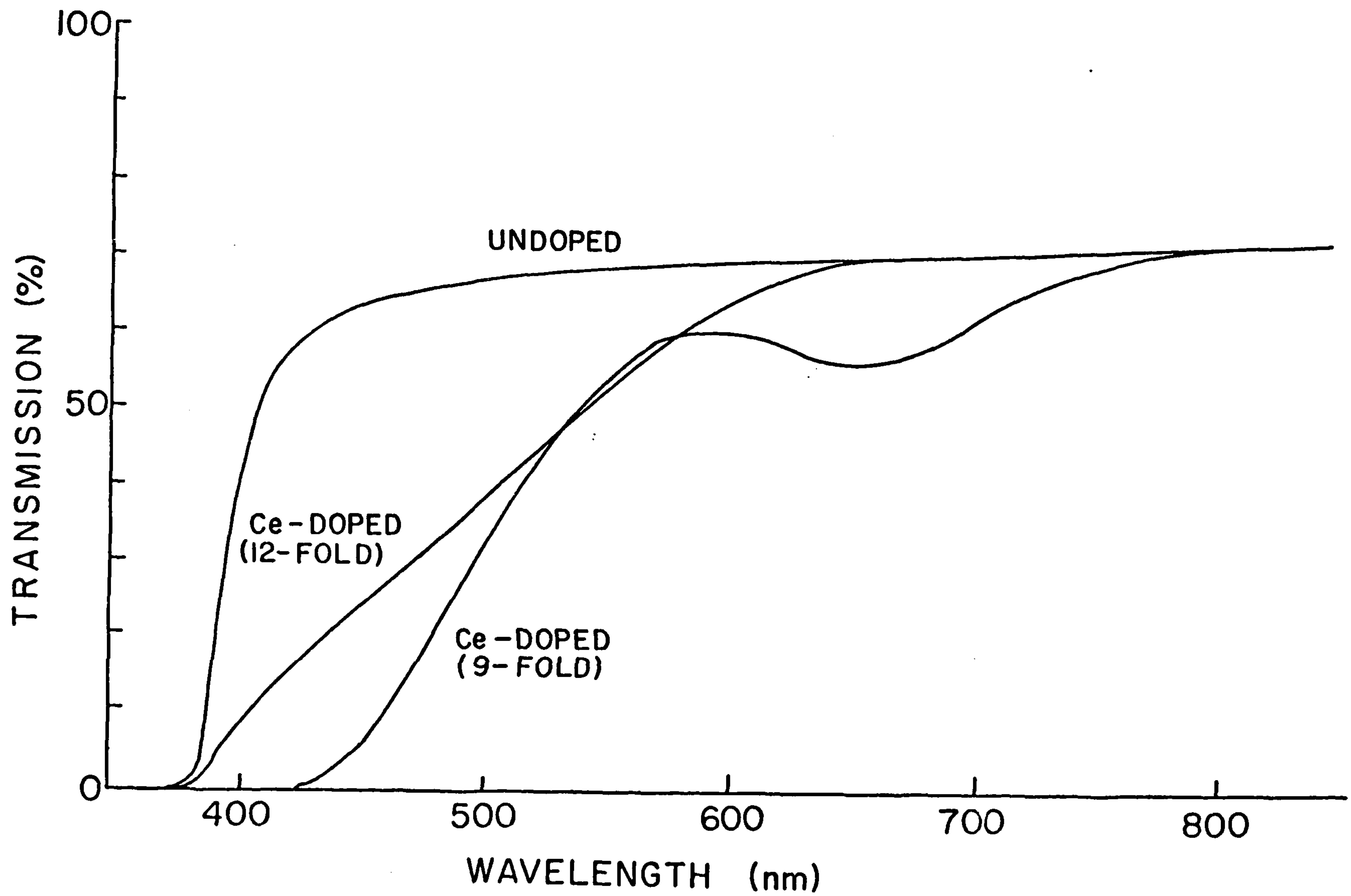


3'
2'
4'
1'
3
2
1
4



$-\bar{k}_1$
$\bar{k}_2$
2θ
$\bar{k}_g = \bar{k}_2 - \bar{k}_1$
READING BEAM
3
4
1
2
2θ
PHASE CONJUGATE SIGNAL BEAM
WRITING BEAMS


C- AXIS
$+\theta$
α_2
α_1
+ POLING ELECTRODE

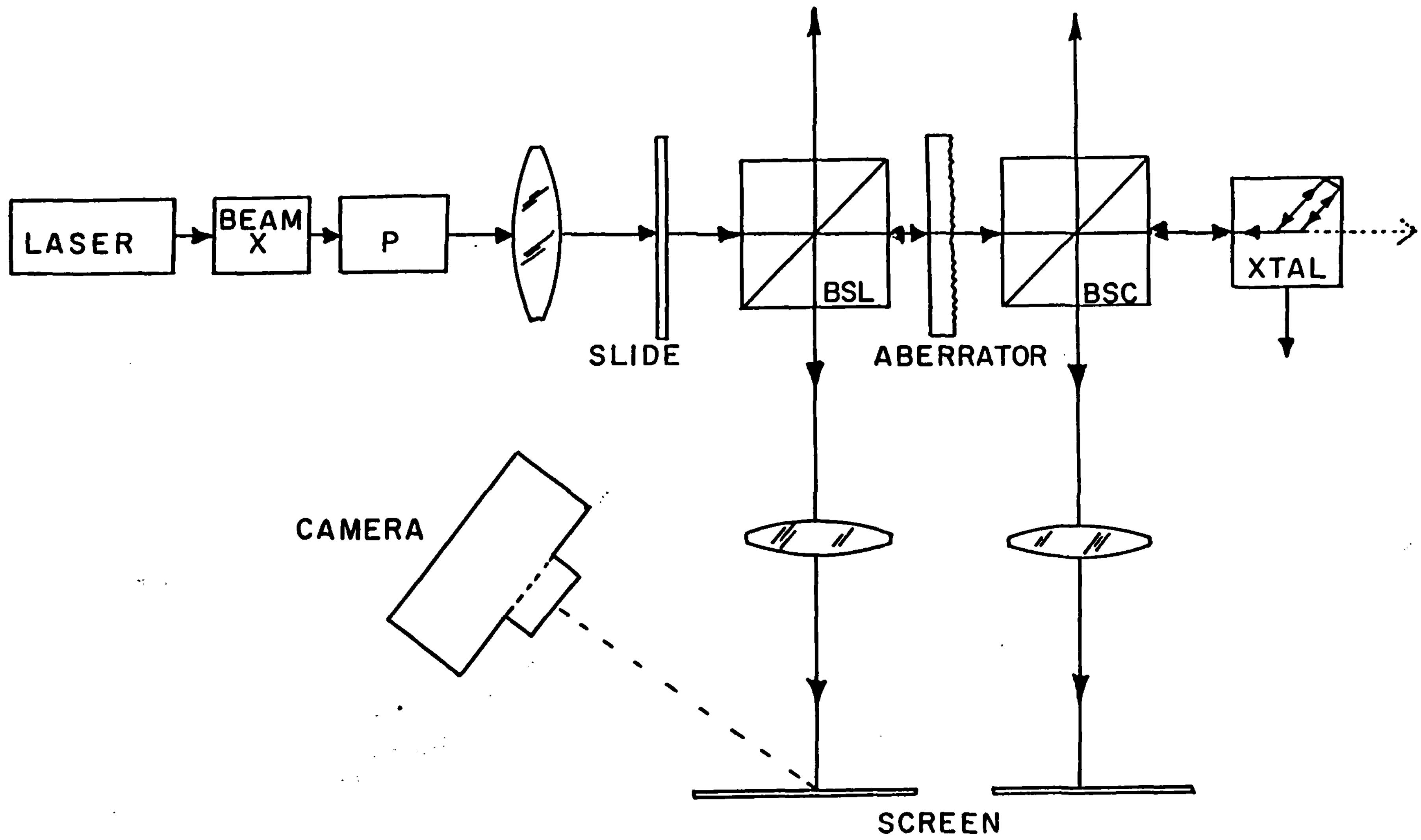

100
50
0
TRANSMISSION (%)
UNDOPED
Ce-DOPED
(12-FOLD)
Ce-DOPED
(9-FOLD)
400
500
600
700
800
WAVELENGTH (nm)

PROPERTY	SBN:60	Ce-SBN:60
DIELECTRIC CONSTANT	$\varepsilon_{11} = 470$ $\varepsilon_{33} = 880$	ε_{11} = --- $\varepsilon_{33} = 1100$
ELECTRO-OPTIC COEFFICIENT $\times 10^{-12}$ m/V	$r_{13} = 55$ $r_{33} = 224$ $r_{42} = 80$	$r_{13} = 55$ $r_{33} = 244$ $r_{42} = 80$
REFRACTIVE INDEX (514.5 nm)	$n_o = 2.367$ $n_e = 2.337$	$n_o = 2.346$ $n_e = 2.310$
BIREFRINGENCE $\Delta n = n_e - n_o$	$\Delta n = -0.03$	$\Delta n = -0.036$
T_c (C°)	75	72
PHOTOREFRACTIVE SENSITIVITY (Cm^2/J)	3.2×10^{-5}	6.5×10^{-3}
RESPONSE TIME (ms)	1000	80
GROWTH TEMPERATURE (C°)	1500	1485
GROWTH DIRECTION	[001]	[001]
COLOR OF CRYSTAL	PALE CREAM	PINK

MATERIAL	WAVELENGTH RANGE OF INVESTIGATION (nm)	WAVELENGTH[1] (nm)	SELF-PUMPED REFLECTIVITY (%)	TIME RESPONSE (sec)		
				Conjugate	Fan	Intensity
SBN:60						
Undoped	442	442	60	---	---	---
Ce-doped	442-633	442	30	---	0.6	0.2 W/cm^2
				---	0.05	2 W/cm^2
Ce-doped[2]	488-730	647	8	120	---	2 W/cm^2
SBN:75						
Ce-doped	442-515	442	6	7.7	2.0	0.2 W/cm^2
				1.6	0.25	2 W/cm^2
BSKNN II						
Ce-Doped	458-515	458	30	279.5	5.8	0.2 W/cm^2
				88.4	0.9	2 W/cm^2
BSKNN III						
Ce-doped[2]	488-780	647	20	1200	---	0.2 W/cm^2
				300	---	2 W/cm^2

[1] This is the wavelength at which the data was taken

[2] Doping consists of cerium in 12-fold coordinated sites except in the cases marked with a 2 where cerium is in the 9-fold coordinated sites

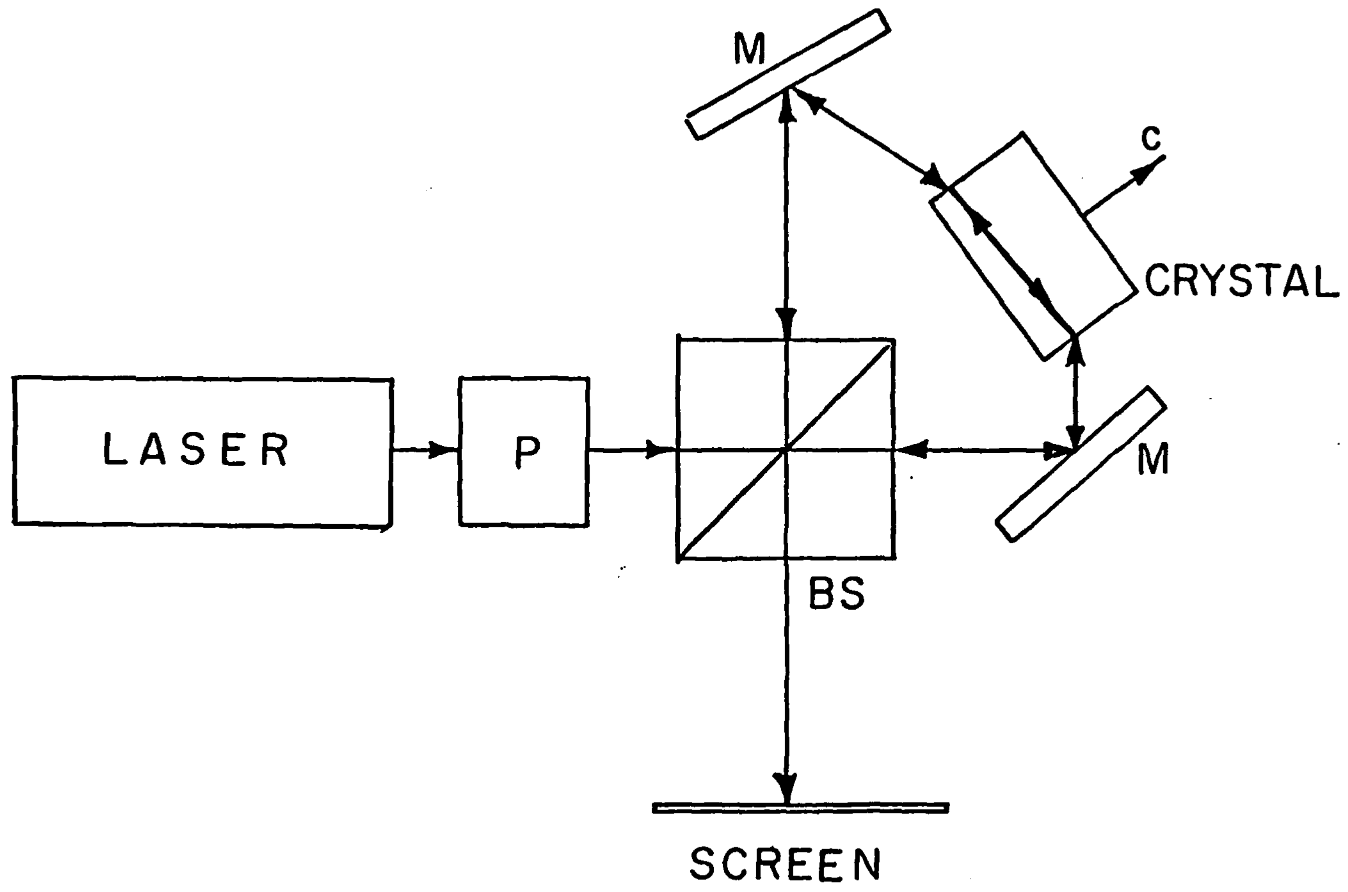

LASER
BEAM X
P
SLIDE
BSL
ABERRATOR
BSC
XTAL
CAMERA
SCREEN

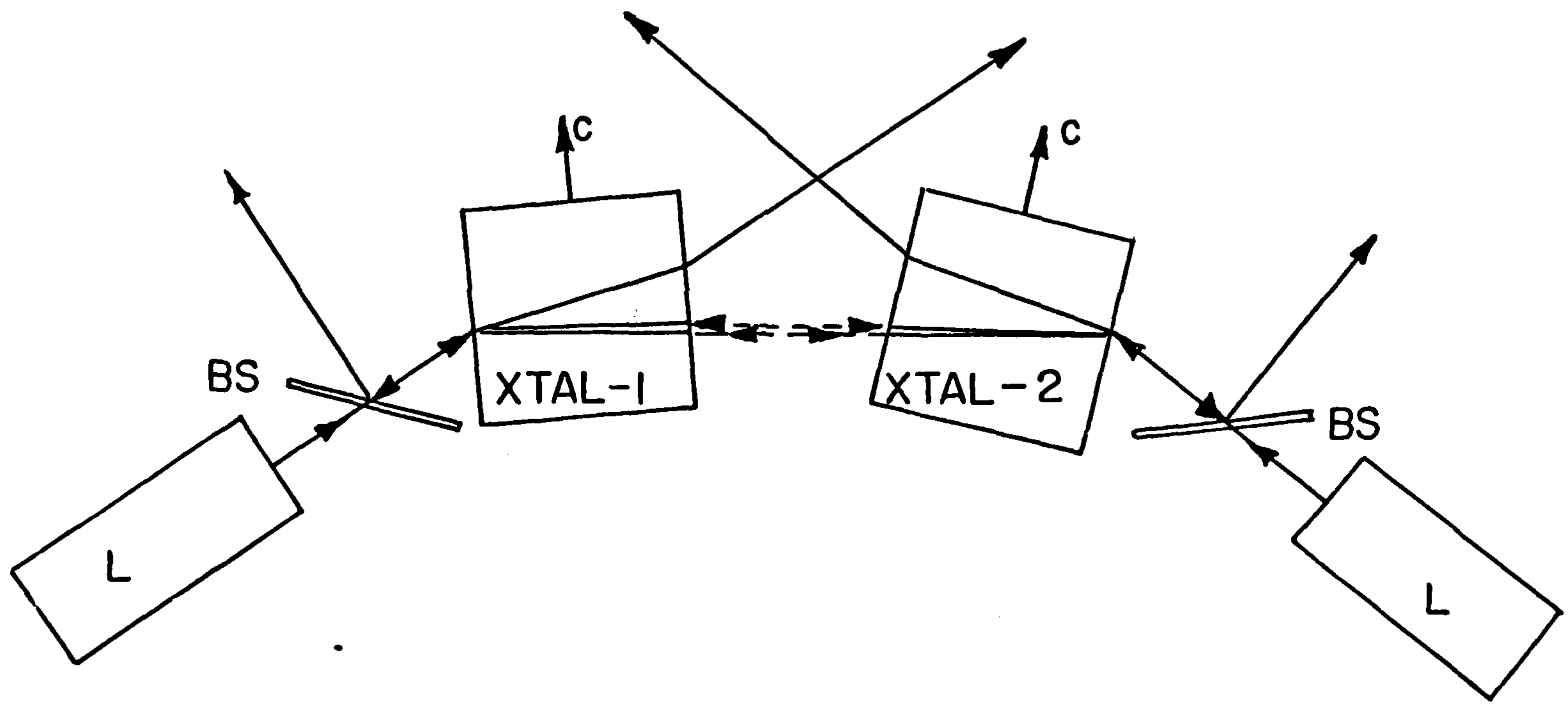
INPUT

CONJUGATE

ABERRATED

CORRECTED


M
c
CRYSTAL
LASER
P
M
BS
SCREEN



c
c
BS
XTAL-1
XTAL-2
BS
L
L

CENTER FOR NIGHT VISION AND ELECTRO-OPTICS

STIMULATED BRILLOUIN SCATTERING FOR DIRECTED ENERGY LASERS

PHASE CONJUGATION TECHNOLOGY EVOLUTION

1972:

- FIRST DISCOVERED IN THE SOVIET UNION:
  ZEL'DOVICH, ET AT, SOVIET PHYSICIST JETP 15, 109 (1972)

1977:

- FIRST WORK IN U.S. REPORTED IN 1977:
  HELLWARTH, J. OPT. SOC. AMER., 67, 1977

1982-83:

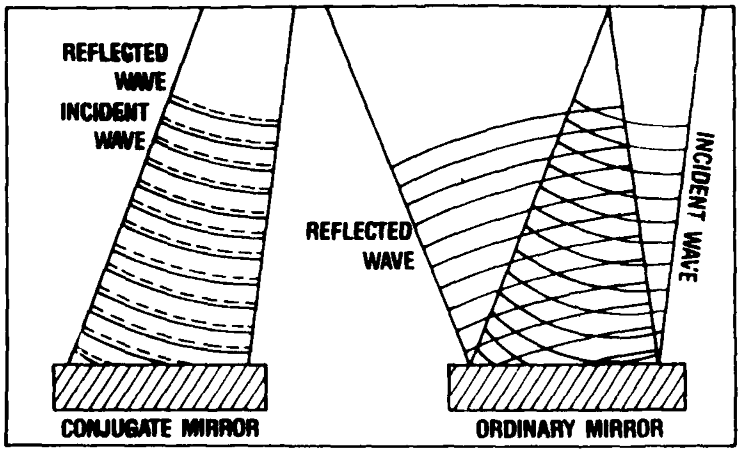
- HUGHES HRL RESULTS IN 1 JOULE, PHASE CONJUGATED LASER DEMO IN LAB

1983-84:

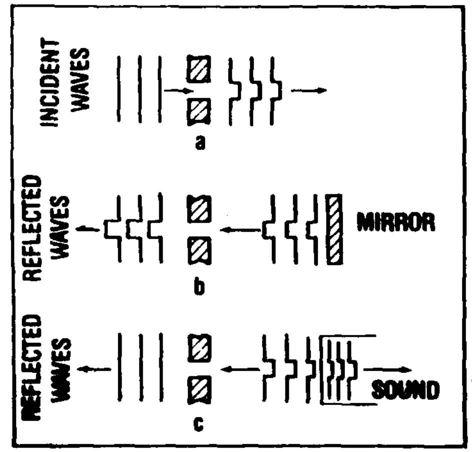
- [illegible] [illegible] PHASE CONJUGATION EXPERIMENTS WITH RESULTING PATENT APPLICATIONS

PRINCIPLES OF OPTICAL PHASE CONJUGATION

ANGULAR COMPENSATION

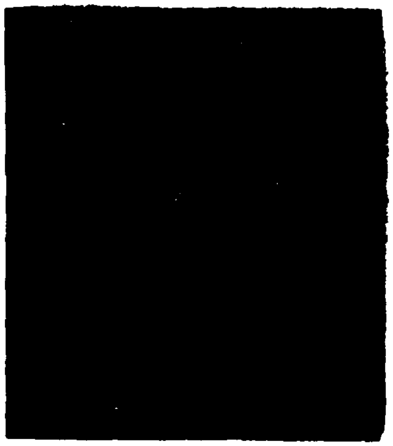


ABERRATION COMPENSATION



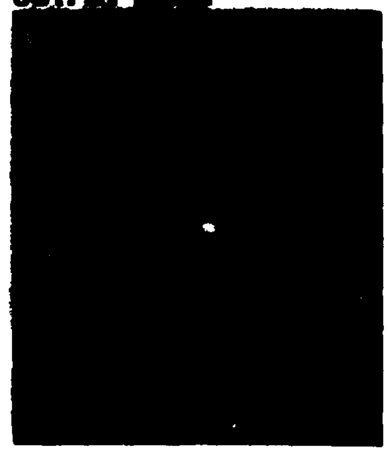
ACOUSTIC WAVE COMPENSATES ABERRATED WAVE

ORIGINAL BEAM

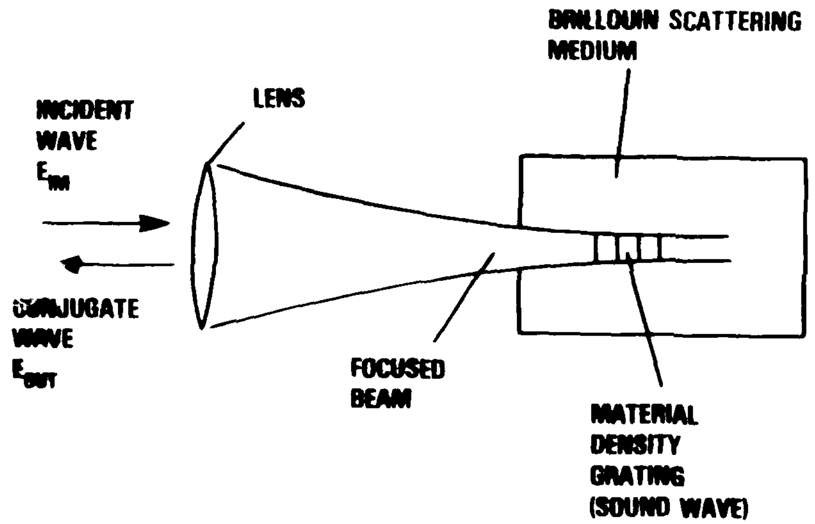


DISTORTED OUTPUT [redacted]

PHASE-CONJUGATED OUTPUT [redacted]



PHASE CONJUGATION IMPLEMENTATION VIA STIMULATED BRILLOUIN SCATTERING



SBS MEDIA SUMMARY:

- ACETONE LIQUID
- CARBON DISULFIDE LIQUID
- <u>METHANE GAS AT 150 ATM</u>
- CARBON TETRACHLORIDE LIQUID
- BENZENE LIQUID
- NITROGEN GAS AT 300 ATM
- CHLOROBENZENE LIQUID
- WATER
- QUARTZ CRYSTAL

SBS PHYSICS: ELECTROSTRICTIVE EFFECT:

DENSITY VARIATIONS ~ ELECTRIC FIELD

RESULT: FORMATION OF DENSITY GRATING (ACOUSTIC WAVE)

WANTS AND REQUIREMENTS

- WANT:

  MORE ENERGY, POWER, BRIGHTNESS.

  LESS WEIGHT, ENERGY CONSUMPTION.

- THIS REQUIRES:

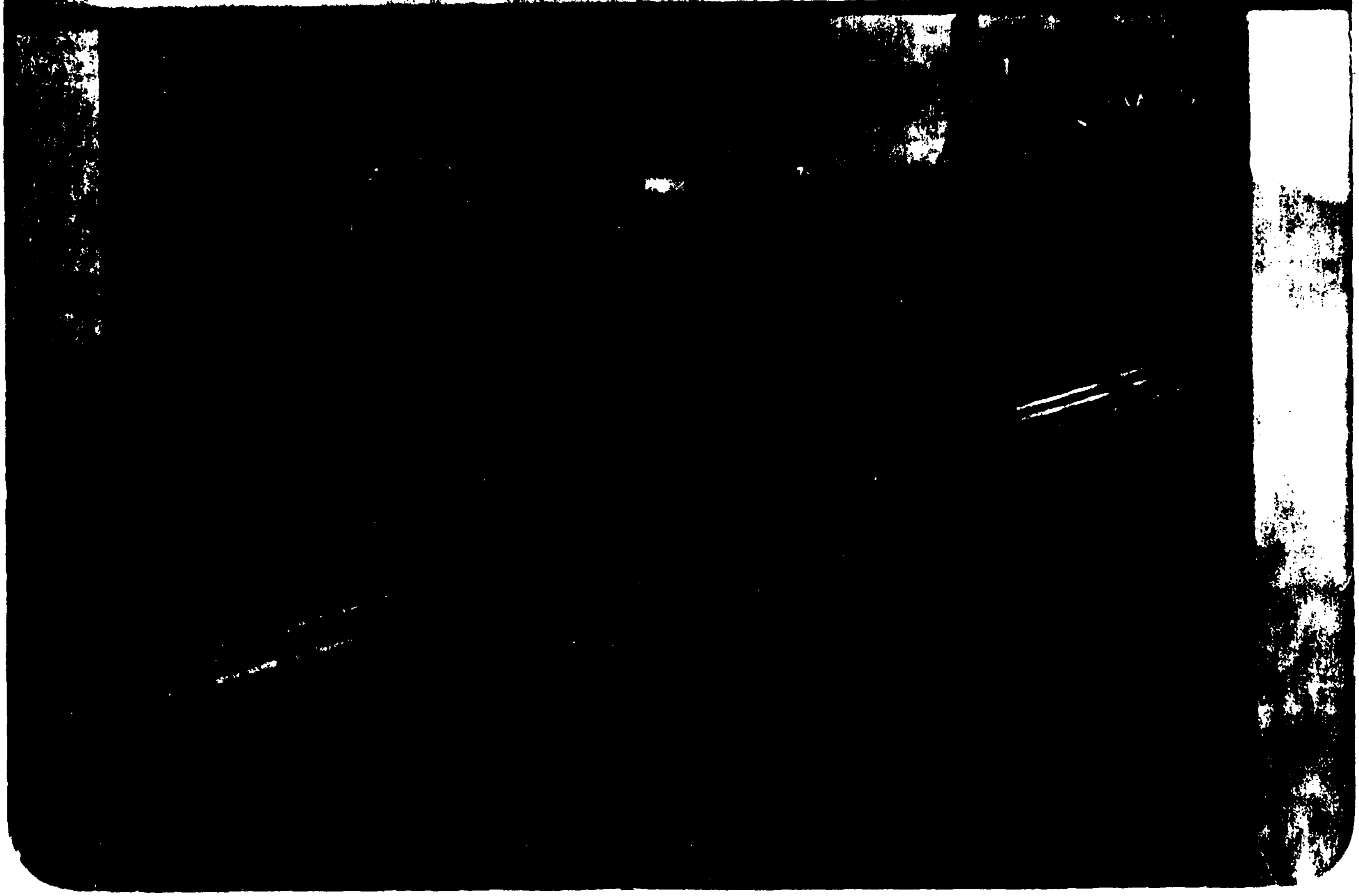
  GREATER LASER EFFICIENCY

PHASE CONJUGATION IMPACT UPON RELIABILITY AND PRODUCIBILITY

- ELIMINATES BEAM WANDER/REDUCES DEMANDS ON BEAM POINTING
- SIGNIFICANT WEIGHT REDUCTION (30%) WITH INCREASED STABILITY
- INCREASED OVERALL EFFICIENCY (1.5-2%)
- ALLOWS USE OF LOWER QUALITY, YAG RODS/COST SAVING
- REDUCED PRODUCTION COSTS DUE TO INHERENT ALIGNMENT (K < LABOR)
- SCALABLE TO JOULE/KILOJOULE LEVEL

PHASE CONJUATE MIRROR

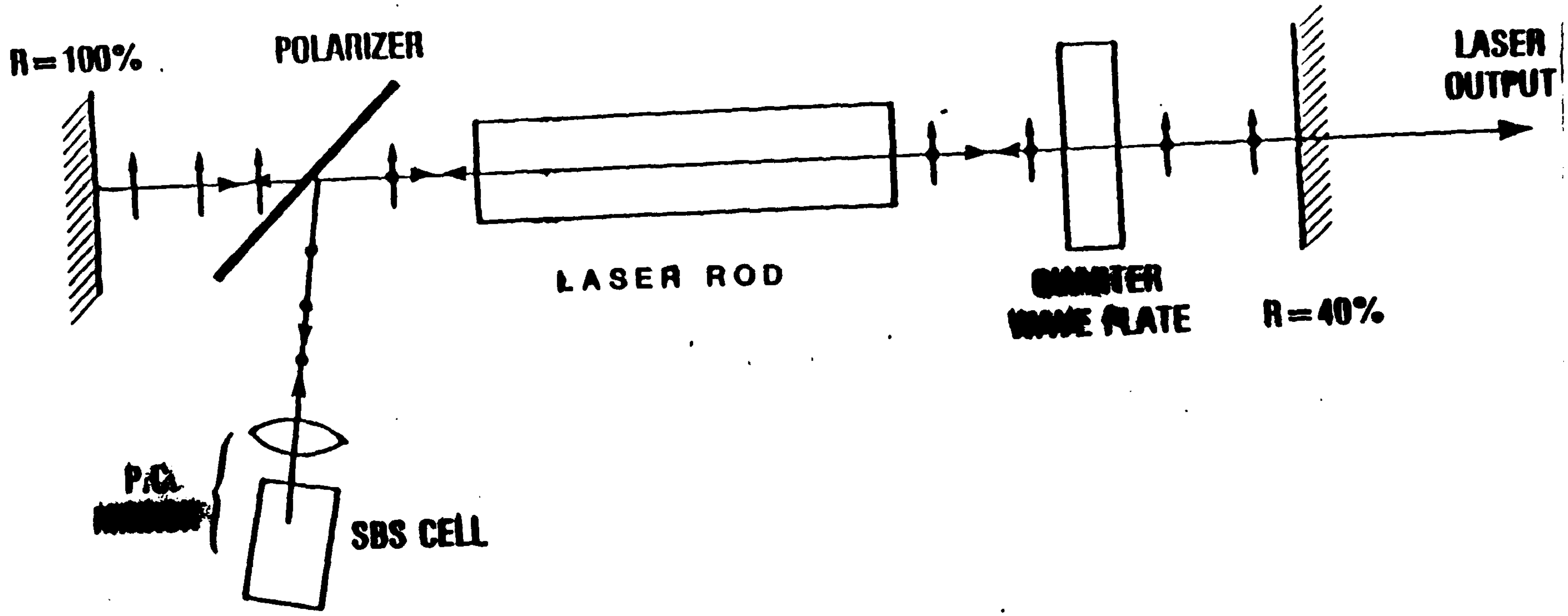
HUGHES



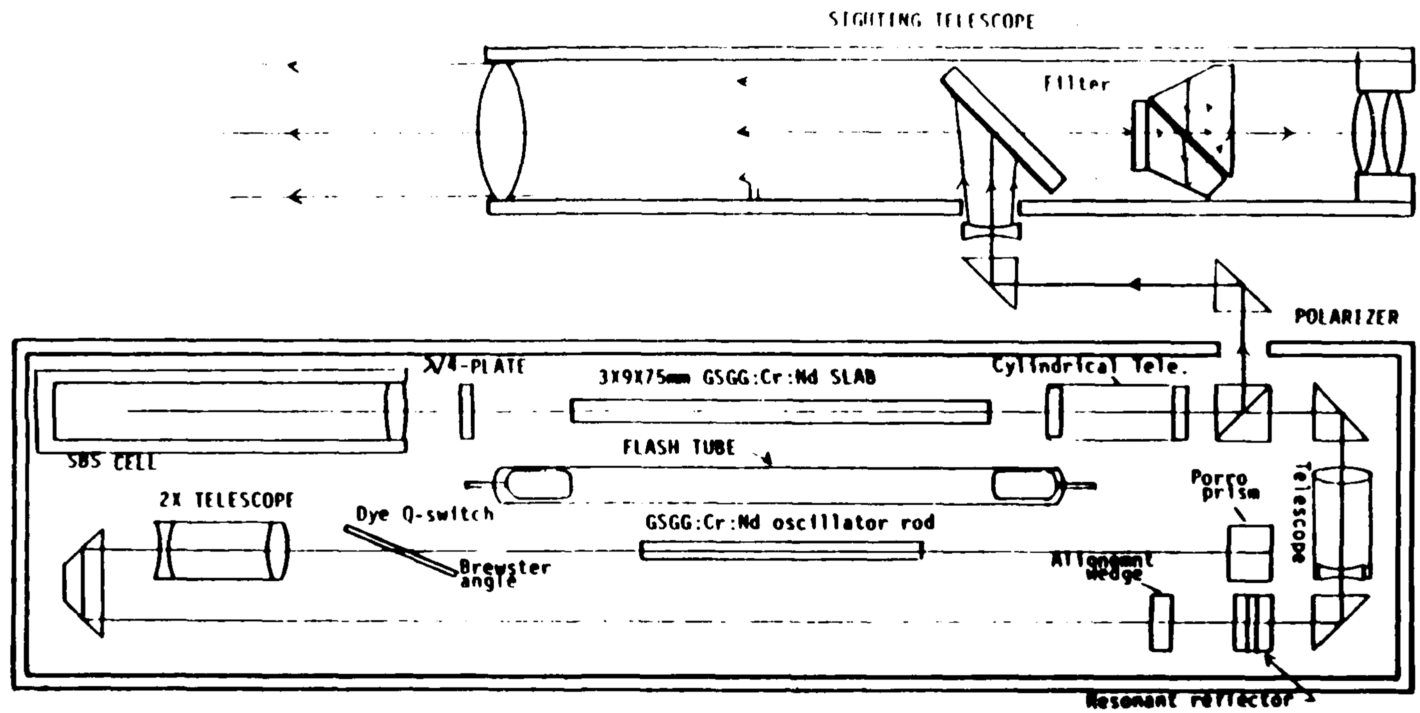
NVEOC PHASE CONJUGATION PATENTS

1. "SIDE ARM PHASE CONJUGATED LASER," #779,762
2. "PHASE CONJUGATED SLAB LASER DESIGNATOR"
3. "PHASE CONJUGATED HYBRID SLAB LASER"
4. "PHASE CONJUGATED FULL APERTURE FOUR PASS LASER AMPLIFIER"

PROPOSED
Q-SWITCH LASER APPARATUS



PHASE CONJUGATED SLAB LASER DESIGNATOR



12

FULL APERTURE FOUR-PASS DESIGN

- BETTER ENERGY EXTRACTION
- POSSIBLE ONLY WITH STRAIGHT-THROUGH SLABS

UNCLASSIFIED

CONSEQUENCE OF THERMAL EFFECTS

- BEAM DEGRADATION DUE TO
  - (A) BIREFRINGENCE
  - (B) WAVEFRONT DISTORTIONS

- BEAM POINTING ERRORS

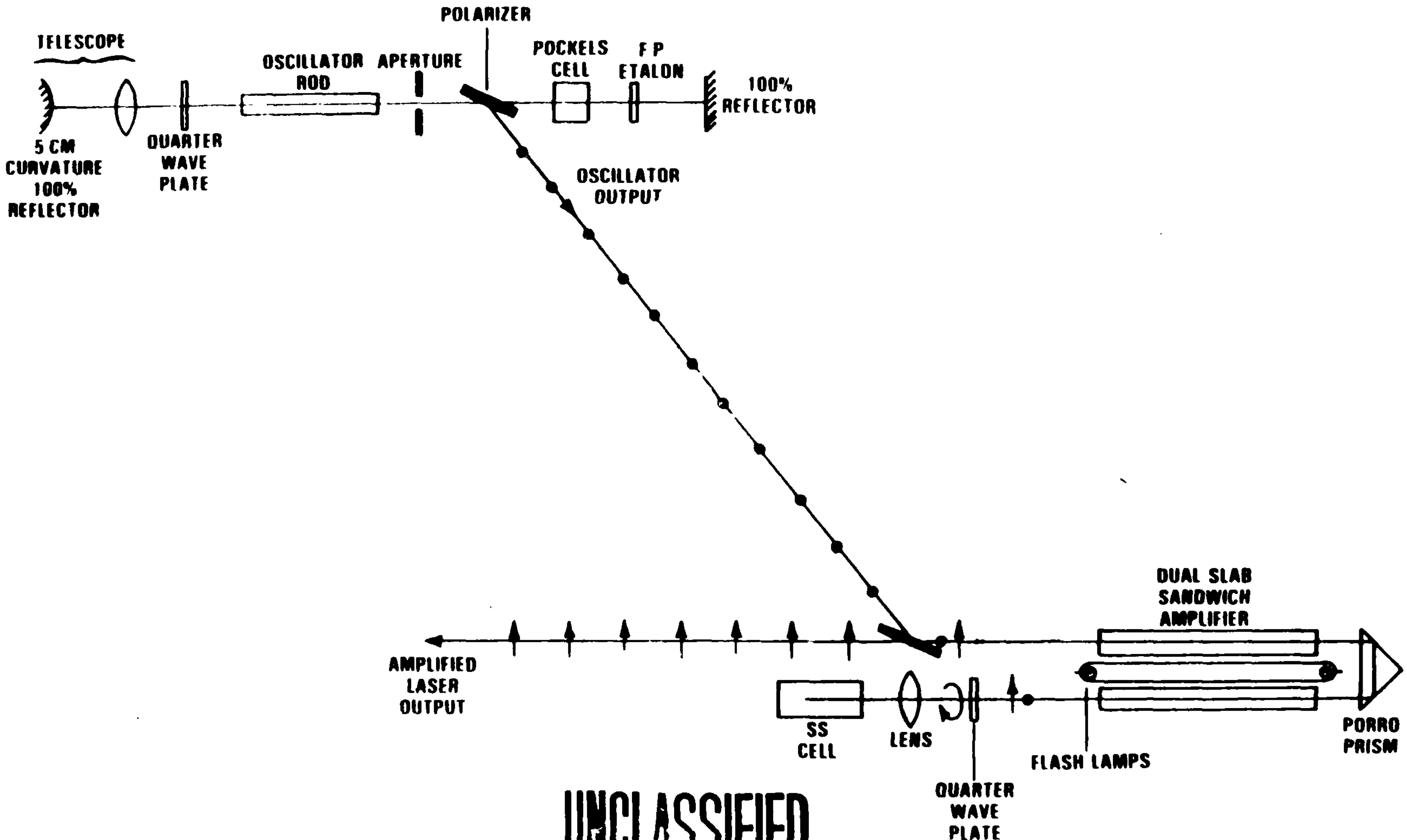
UNCLASSIFIED

DESIGN APPROACH

- OSCILLATOR-AMPLIFIER
- SLAB
- PHASE CONJUGATION
- SANDWITCH PUMPING DESIGN
- FULL APERTURE FOUR-BEAM PASSES

13

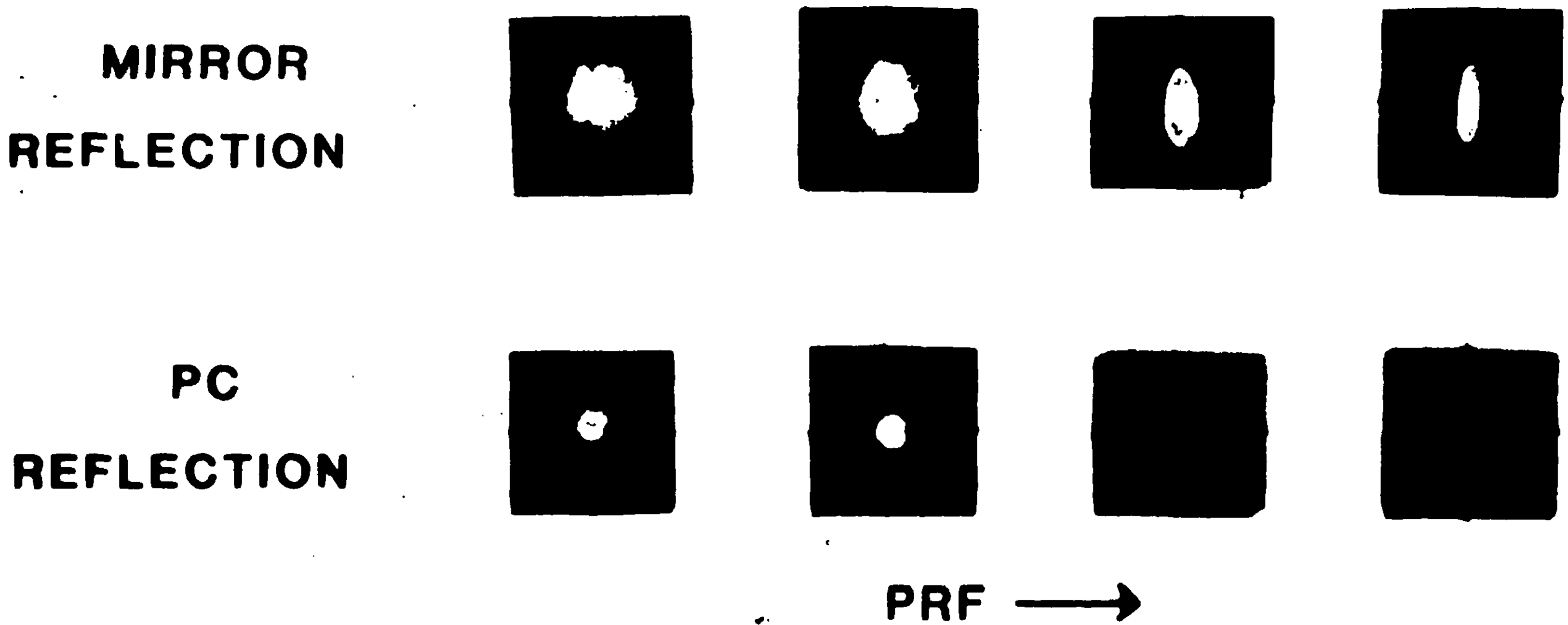
UNCLASSIFIED



UNCLASSIFIED

UNCLASSIFIED

MIRROR VS. PC REFLECTED AMPLIFICATION



UNCLASSIFIED

PHASE CONJUGATION WORKSHOP
TECHNICAL ISSUES

- COMPETING PROCESSES
- SCALING ISSUES (CONFIGURATION)
- ALTERNATIVE MEDIA (GLASSES)
- FIDELITY

CNVEO & U of R

5. LIST OF ATTENDEES

Electro-Optic Workshop

22 March 1988

Dr. Rohde	CNVEO
L.N. Durrasula	CNVEO
Robert Boyd	Univ of Roch
Suresh Chandra	CNVEO
John Pollard	CNVEO
Mark Norton	CNVEO
James Habersat	CNVEO
Tom Stone	Univ of Roch
Ken MacDonald	Univ of Roch
Nicholas George	Univ of Roch
Rich Utano	CNVEO
Wayne Hovis	CNVEO
Dr. Buser	CNVEO
Susan St. Cyr	Polaroid

END
DATE
FILMED
DTIC
9-88